# SUPERPAVE LEVEL ONE MIX DESIGN AT THE LOCAL GOVERNMENT LEVEL

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Mark P. Hanson

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# CHAPTER ONE

# INTRODUCTION

## Motivation

The SHRP Superpave asphalt mixture design system, with its stringent material requirements was specifically developed to produce pavements to meet the expectations of the American public. The Superpave system includes a performance graded asphalt binder system, criteria for aggregate properties, a new mix design procedure using the Superpave gyratory compactor, and refined procedures and requirements for mixture analysis. To date, the Superpave system has primarily been used on medium to high volume roadways, where funding is more readily available. Issues concerning aggregate availability and local economy have limited its use on low-volume roads at the local government level. Therefore, the question is: Can the material and testing requirements of the Superpave system be economically applied at the local government level without compromising pavement performance? To answer the above question, the two key requirements of the Superpave system, material requirements and testing requirements, were evaluated.

## Relationship to Previous Work

The Superpave system has existed since 1987 when it was developed by the Strategic Highway Research Program (Asphalt Institute, 1996). It has been used with varying degrees of success by several State Departments of Transportation on high-volume roads such as urban interstates. Due to its high material and construction costs relative to other mix design systems, however, its use at the local government level has yet to be widely accepted. The results of this research presents a slightly modified Superpave system for use at the local level for low-volume roadways in the state of Minnesota.

## Objective

The intent of this research was to investigate the feasibility of using the Superpave Level One mix design system at the local government level for use on low-volume roadways in the state of Minnesota. The effects of different gradations, aggregate sources, and asphalt performance grades were evaluated.

## Scope

Two different aggregate gradations were evaluated: coarse and fine. The fine aggregate (passing the 9.5 mm (3/8 in.) sieve) in all mixes was composed solely of a sand from Lakeland, Minnesota—a very readily available, low-cost aggregate. Four different coarse aggregates (retained on the 12.5 mm (1/2 in.) and 9.5 mm (3/8 in.) sieves) were evaluated: Granite Falls granite, New Ulm quartzite, Kasota limestone, and Cedar Grove gravel—all readily available at varying costs. Lastly, the effects of two different asphalt performance grades (PG 52-34 and PG 58-40) were evaluated. A Brovold gyratory compactor was used to prepare all samples.

## Organization of Report

This report is arranged into five sections: Introduction, Literature Review, Research Methodology, Results and Discussion, and Conclusions and Recommendations. The Literature Review provides a background on the mechanics of asphalt compaction, the importance of volumetrics, and current mix design methods—with special emphasis on the Superpave method. Research Methodology discusses the aggregate properties, laboratory mixtures, gyratory compactor, compaction procedure, and data analysis methods. Results and Discussion presents the results of the mix design, resilient modulus test, and moisture sensitivity tests and discusses their significance. The report closes with some final conclusions and recommendations. Literature sources used as supporting references are cited in the bibliography and additional summarized test data are provided in the appendices.

# CHAPTER TWO

# LITERATURE REVIEW

## INTRODUCTION

The purpose of compaction is to densify an asphalt pavement. Resistance to shear deformation cannot be developed without close contact of the aggregate particles in the mix. The close contact of the particles allows the development of interparticle friction necessary to resist displacement of the mix under load. Likewise, the development of a high degree of impermeability results only when a well-designed and manufactured mix is thoroughly compacted. It has been conclusively shown that the durability of the pavement is directly related to permeability—the amount of air and water passing through the mix. Exposure to air may cause oxidation of the asphalt leading to premature hardening of the pavement and a susceptibility to cracking and stripping. Unless the compactive effort has placed the particles close enough together, the tensile strength of a mix cannot be developed by the cohesiveness of the asphalt films coating each particle (Marker 1967). Simply stated, a tough, durable, smooth pavement can only be accomplished with proper compaction.

## COMPACTION

A pavement's resistance to shear is a function of the cohesive, internal friction and confining forces within the asphalt mix. These forces are best illustrated by Mohr's Circle (Figure 2.1), where Coulomb's equation is used to calculate shear strength:

$$\tau = c + \sigma \tan \phi \qquad (2.1)$$

Where

$\tau$ = shear stress
c = cohesion
$\sigma$ = confining pressure
$\phi$ = angle of internal friction

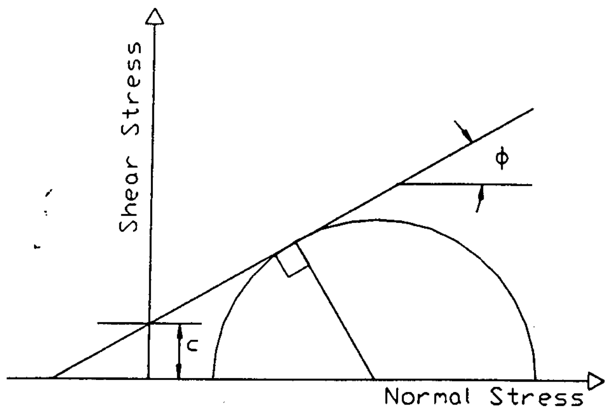


Figure 2.1 Mohr's Circle

The basic principles of asphalt compaction are similar to soil compaction. Soil compaction occurs in several ways: reorientation of particles; fracture of the bonds between them (followed by reorientation); and distortion of the particles and their adsorbed layers (Sowers 1970). Cohesive soil densification is primarily the result of distortion and particle reorientation. The fracturing and reorientation of particles enables densification of cohesionless soils such as crushed rock. The internal friction between particles, however, resists particle reorientation. Therefore, increasing aggregate angularity increases the material's resistance to densification.

The moisture content of soils, similar to asphalt content in hot mix asphalt, plays an important role in densification. In cohesive materials, the interparticle cohesive forces decrease as moisture content increases. Increasing moisture content in cohesionless materials cause the capillary tension between particle grains to decrease. The resulting decrease in interparticle contact pressures decreases the internal friction of the soil (Sowers

1970). Increases in moisture contents to optimum levels prior to compaction results in the most effective compactive effort.

Another important element of effective compaction is lateral confinement of the material. In the laboratory, confinement of the mixture is achieved via the mold. In the field, the flow properties of the material must enable adequate resistance to lateral flow. Without lateral flow confinement, vertical compression cannot take place (Geller 1984). The confining ability of pneumatic (rubber-tire) rollers makes them ideal for compacting tender mixtures.

Geller (1984) cites Nijboer's (1948) explanation of the three primary forces resisting compaction within hot mix asphalt:

1. the angle of internal friction (frictional resistance)
2. the initial resistance (cohesive and interlocking resistances)
3. the viscous resistance (viscosity of the mix times rate of flow)

The first resistance, angle of internal friction, is primarily a function of the aggregate properties. The second, initial resistance, is a function of the bitumen and filler properties acting as a thin film coating the aggregate, the interlocking action of the particle shapes comes into effect toward the completion of the compaction process. Viscous resistance is a function of both aggregate and binder properties.

In the field, the rolling of a hot asphalt concrete pavement provides a means of applying vertical pressure and kneading action to a mix enabling densification to occur (Kari 1967). The conditions existing under a moving roller are shown in Figure 2.2. The roller wheel or tires sink into the asphalt mix until the contact area is large enough to reduce the contact pressure of the wheel to approximately that of the mix's bearing capacity. The roller wheel's motion creates shear forces within the asphalt. The horizontal shear forces developed in the front and rear of the roller create zones of decompaction within the pavement. The vertical shear forces developed directly underneath the roller wheel create a zone of compaction.

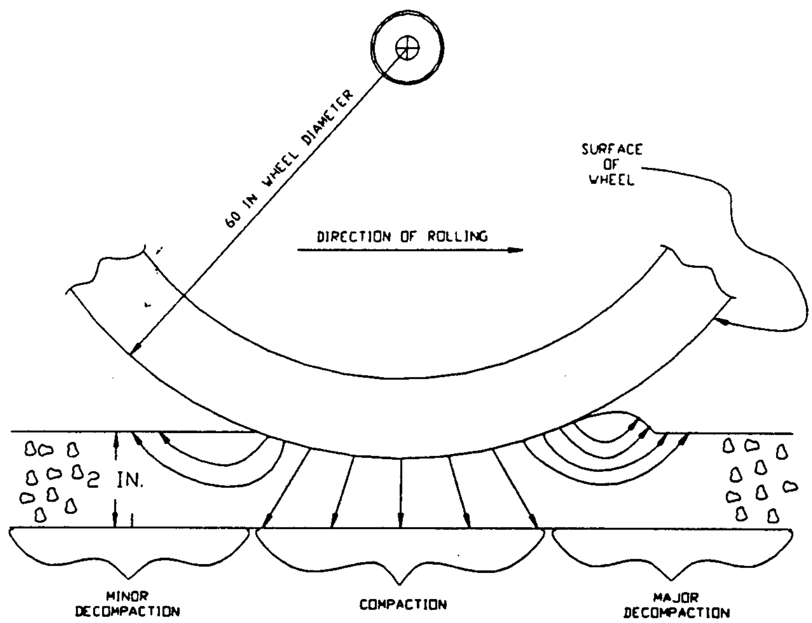


Figure 2.2 Compaction Process (After Kari, 1967)

Kari (1967) describes two unfavorable compaction conditions: understressed and overstressed. A mix is understressed when the bearing capacity of the mixture is greater than the contact pressure applied by the roller—the roller simply rides on top of the mix without any compaction taking place (Figure 2.3). A mix is overstressed when it cannot support the weight of the roller—the roller sinks deep into the mix resulting in shoving and severe cracking but little to no densification. Thus, the bearing capacity of the mix and the roller weight and configuration must complement each other to achieve maximum density and toughness.

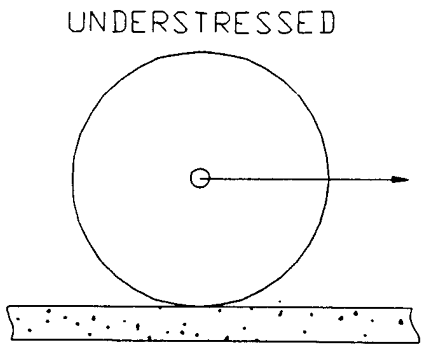


Figure 2.3 Understressed and Overstressed Conditions (After Kari, 1967)

## MATERIALS EVALUATION AND THEIR AFFECT ON COMPACTION

### Binder

The asphalt binder is considered a viscoelastic material because it exhibits properties of both a viscous and an elastic material. As such, the asphalt binder affects compaction in a variety of ways. The viscosity of asphalt is extremely temperature dependent: at room temperature asphalt is virtually a solid, above 121°C it is a fluid. Increasing the temperature of a mixture decreases the binder's viscosity causing a reduction in the overall stiffness of the mix. If a mix is too hot, it will be tender and move laterally from underneath the roller. Conversely, as the mix cools, it stiffens, requiring a greater compactive effort to densify it.

The influence of the binder on an asphalt mixture's resistance to compaction was shown in a study by McLeod (1967). A high viscosity asphalt cement at a typical placement temperature of 135°C has a viscosity of approximately 5 poise. The viscosity of the same asphalt cement at 63°C, when rolling often ends, was 5000 poise—a 1000-fold increase. The respective Marshall stabilities of the mix at the two temperatures were 667N and 6672—a 10-fold increase. In only a 72°C temperature difference, a 1000-fold increase in the binder's viscosity resulted in a 10-fold increase in the mix's strength.

## Aggregate

Gradation, surface texture and angularity are the primary aggregate characteristics affecting the workability and resistance to compaction of a mix. Larger aggregate sizes and/or higher coarse aggregate percentages result in lower workability and higher compactive efforts. Likewise, a rough surface texture, as opposed to a smooth, glassy texture, results in a stiffer, less workable mix. Using highly angular coarse and fine aggregate results in a high degree of internal friction (and thus, high shear strength), increasing the resistance of the mix to permanent deformation. Limiting the percentage of elongated particles minimizes the potential for aggregate crushing during mixing and construction (Asphalt Institute 1996).

If workability is too low, rounded sands are often added to increase the mix's workability. However, too much rounded sand results in tender mixes—mixes with high workability but low stability. Tender mixes are often easily overstressed by heavy rollers and over-rolling resulting in the lateral movement of the mix from under the roller.

## Filler

Fines, or filler content, affect the compactiblity of a mix because they combine with the asphalt cement to provide the binding, cohesive forces of the mix. Filler material increases the effective viscosity of the binder matrix, effectively creating a mastic. Page: 9
Kari (1967) cites Santucci and Schmidt (1952) when he explains there exists an optimum filler content for maximum compaction (Figure 2.4). A study by Bissada (1984) showed higher filler contents resulted in higher stiffness values achieved at lower resistances to compaction. Additionally, filler will help offset the tenderness of mixes with too much sand. However, too much filler results in "gummy" mixes that are difficult to compact.

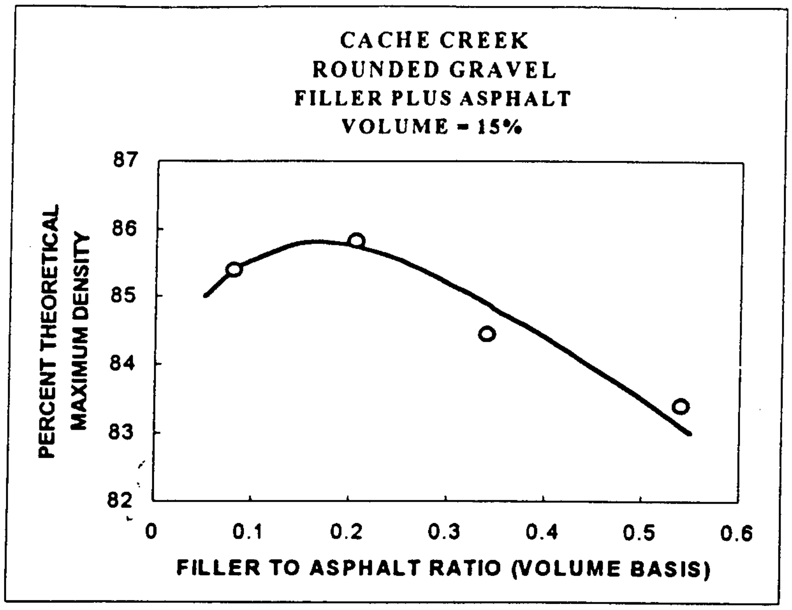


Figure 2.4 Filler to Asphalt Ratio Influences Compactive Effort
(After Santucci & Schmidt, 1952)

## FACTORS AFFECTING COMPACTION

### Mix Properties

At higher temperatures, the lower viscosity of the asphalt cement causes it to act as a liquid, allowing the aggregate particles to effectively interlock. At slightly lower temperatures, the binder acts as a lubricant permitting the aggregate to shift and densify during compaction. Further reduction in temperature results in a stiffening of the binder where its cohesion will prevent further densification.

As the asphalt content increases, so does the film thickness of the asphalt on the aggregate. At compaction temperatures, the thicker films increase the lubricating effect of the asphalt. Additionally, a study by Harvey and Tsai (1996) showed pavement overlay life increased 10 to 20 percent with each 0.5% increase in asphalt content (when compacted to the same air void content) with respect to fatigue. If asphalt contents are excessive, however, the resulting tender mix will bleed.

The temperature of the mix affects the compaction process in much the same way as asphalt content. As previously discussed, the workability of the mix increases as the temperature of the mix increases. The upper limit for mix temperature is approximately 150°C (300°F); temperatures above 150°C may result in damage to the asphalt by accelerated hardening. The lower limit for effective compaction is approximately 85°C (185°F); below which great compactive effort is required for little to no gain in densification of the mix. Figure 2.5 shows the effect of compaction temperature on void content (Parker, 1960) using a Marshall compactor at 50-blows per side. Parker's work showed compaction at 300°F (150°C) yielded an air void content four times greater than compaction at 275°F (135°C).

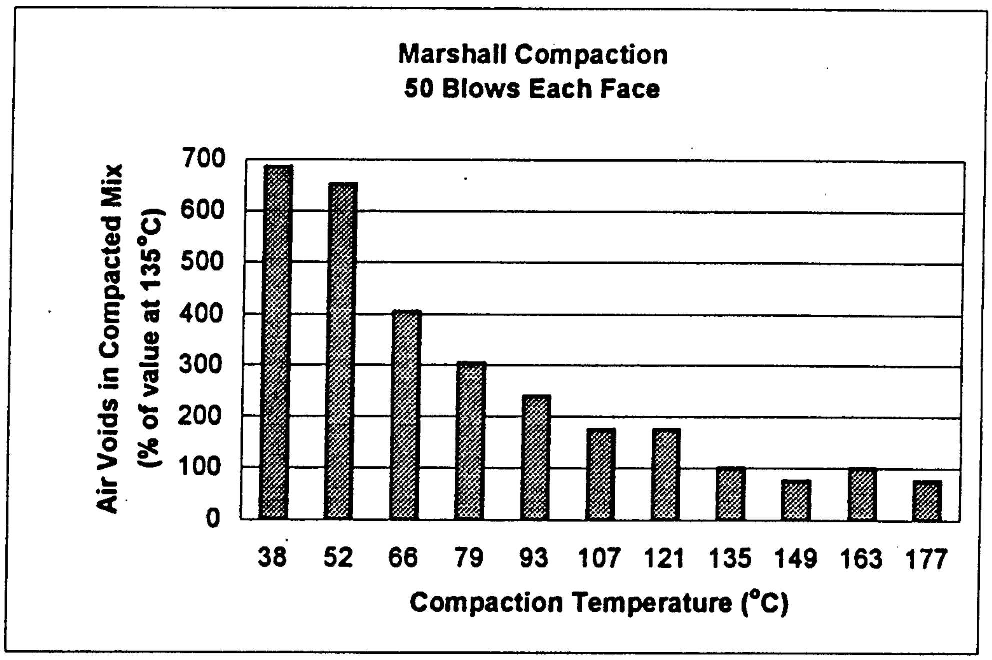


Figure 2.5 Influence of Compaction Temperature on Percent Air Voids
(After Parker, 1960)

A study by Kennedy et al. (1984) showed that low temperatures during compaction have an adverse effect on the engineering properties such as tensile strength, resilient modulus and Marshal stability of an asphalt concrete resulting in reduced pavement performance. Hadley (1970) found that of seven factors studied (aggregate type, aggregate gradation, asphalt cement, asphalt content, mixing temperature, compaction temperature, and curing temperature), compaction temperature dominated the results. Kennedy et al. concluded tensile strength, static and resilient moduli, Marshall stability, and Hveem stability of asphalt are all reduced when compaction occurs at lower temperatures. Temperatures in excess of 155°C (310°F), however, can cause compaction problems (lateral movement) and increase oxidation of the binder which can result in hard and brittle pavements (Brown 1984).

**Environmental**

The rate at which an asphalt mix cools directly affects the length of time during which density can and must be achieved (Asphalt Institute 1989). The ambient air temperature, humidity, wind velocity and the surface temperature under the mix all affect the rate of cooling of a freshly placed asphalt layer. Cool air temperatures, high humidity, strong winds, and cool surfaces either alone or together adversely shrink the effective compaction window.

**Layer (Lift) Thickness**

Thicker asphalt layers retain heat longer. Therefore, less compactive effort is required to achieve target density in thicker asphalt layers than in thinner layers. The heat-retaining ability of larger lifts make their use desirable when placing stiffer mixes or when paving in adverse environmental conditions. The retained heat of thicker lifts also permits lower paving temperatures, so either lower mixing temperatures or longer hauling distances are possible (Asphalt Institute 1989). A summary of the factors affecting compaction and their corrective actions can be found in Table 2.1.

Table 2.1 Summary of Influence on Compaction (Asphalt Institute 1989)

| ITEM | EFFECT | CORRECTIONS* |
|---|---|---|
| | **Aggregate** | |
| Smooth Surfaced | Low interparticle friction | Use light rollers<br>Lower mix temperature |
| Rough Surfaced | High interparticle friction | Use heavy rollers |
| Unsound | Breaks under steel-wheeled rollers | Use sound aggregate<br>Use pneumatic rollers |
| Absorptive | Dries mix—difficult to compact | Increase asphalt in mix |
| | **Asphalt** | |
| Viscosity-High | Particle movement restricted | Use heavy rollers<br>Increase temperature |
| Viscosity-Low | Particles move easily during compaction | Use light rollers<br>Decrease temperature |
| Quantity-High | Unstable and plastic under roller | Decrease asphalt in mix |
| Quantity-Low | Reduced lubrication—difficult compaction | Increase asphalt in mix<br>Use heavy rollers |
| | **Mix** | |
| Excess Coarse Aggregate | Harsh mix—difficult to compact | Use heavy rollers |
| Oversanded | Too workable—difficult to compact | Reduce sand in mix<br>Use light rollers |
| Too Much Filler | Stiffens mix—difficult to compact | Reduce filler in mix<br>Use heavy rollers |
| Too Little Filler | Low cohesion—mix may come apart | Increase filler in mix |
| | **Mix Temperature** | |
| High | Difficult to compact—mix lacks cohesion | Decrease mixing temperature |
| Low | Difficult to compact—mix too stiff | Increase mixing temperature |
| **Coarse Thickness** | | |
| Thick Lifts | Hold heat—more time to compact | Roll normally |
| Thin Lifts | Lose heat—less time to compact | Roll before mix cools<br>Increase mix temperature |
| | **Weather Conditions** | |
| Low Air Temperature | Cools mix rapidly | Roll before mix cools<br>Increase mix temperature<br>Increase lift thickness |
| Low Surface Temperature | Cools mix rapidly | Roll before mix cools<br>Increase mix temperature<br>Increase lift thickness |
| Wind | Cools mix-crusts surface | Roll before mix cools<br>Increase mix temperature<br>Increase lift thickness |

## VOLUMETRIC PROPERTIES

Characterization of asphalt mixtures generally consists of several volumetric properties including voids in the total mix (VTM), voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). The most important property in construction is VTM, or air voids, a direct relation to density. A mix having 4% air voids has a density of 96% of maximum. Research and past performance have shown a final compacted void content of 4% is ideal for most dense-graded mixtures. Generally, mixes having low compacted air voids (less than 3%) will be unstable and exhibit premature rutting. Mixes having high air voids (greater than 8%) will generally be permeable to water leading to an increased oxidation rate resulting in premature raveling and/or cracking. It is important to note, however, that these figures are nothing more than generalizations. It is quite possible to have an outstanding, long-lasting pavement that compacted to 98% density (2% air voids).

VMA, the void space in the aggregate, and probably the most important volumetric property in design, is primarily a function of aggregate gradation, particle shape and surface texture. Since VMA includes air voids (it is the sum of VTM and VFA), low VMA indicates low film coating on the aggregate because there is not enough void space for the asphalt to adequately coat the particles without overfilling the void space (Roberts et al. 1996). Since overfilling the void space is the same as having a low VTM, premature and excessive rutting can result.

Although of great importance in volumetric proportioning, as the difference between VTM and VMA, VFA is typically not mentioned in volumetric discussions. However, for the purposes of generalities, typical VFA values range from 50-70% (Roberts et al. 1996).

When VFA exceeds 80-85%, the voids are considered overfilled (with asphalt) resulting in the low stability problems explained above.

## VOID CONTENT

A study by Bell et al. (1984), showed that percent compaction (or void content) was the most significant factor affecting mix performance. As shown in Table 2.2, an increase in void content is associated with a decrease in modulus, fatigue life, and resistance to permanent deformation.

Table 2.2 Effect of Compaction on Hot Mix Asphalt Pavements (Bell et al., 1984)

| | | | $10^7$ ESAL Normal Design Life | | | |
|---|---|---|---|---|---|---|
| Compaction Rating | Voids Content, % | Resilient Modulus, MPa | Horizontal Strain at ACC Bottom | Est Fatigue Life, # Loads to Fail, $10^6$ | Vertical Strain at Subgrade Surface | Est Perm Deform Life, # Loads to Fail, $10^6$ |
| Excellent | 4 | 3370 | 75 | 110 | 200 | 48 |
| Good | 8 | 2060 | 100 | 12 | 245 | 21 |
| Poor | 12 | 1430 | 120 | 2.6 | 280 | 12 |

High stiffness (resilient modulus) values are essential to long-lasting, superior performing hot mix asphalt pavements. The stiffness of a pavement is directly related to the resulting horizontal and vertical strains in the pavement resulting from vehicle loads. Pavements with higher stiffness values exhibit lower strains under the same vehicle loads. Horizontal and vertical strains are important in predicting pavement performance because they directly correlate to fatigue and permanent. The accurate estimation of fundamental engineering properties by the consistent simulation of field compaction is key to a laboratory compaction method's (Hveem, Marshall, gyratory) value in the prediction of long-term pavement performance.

The Asphalt Institute found that changes in stiffness and void content affected fatigue life according to the following expression:

$$N_f = 18.4(C)\times\left(4.32\times10^{-3} \in_t^{-3.29} E^{-0.854}\right) \qquad (2.2)$$

where

$N_f$ = number of load applications to failure
C = a factor dependent on the asphalt and void contents
$\in_t$ = tensile strain,
E = modulus of asphalt mixture

Bell et al. (1984) used the above equation to calculate the fatigue values shown in Table 2. The table clearly shows the profound effect void content has on fatigue life. A 50% reduction in void content from eight to four percent air voids results in nearly a 10-fold increase in fatigue life.

Permanent deformation of flexible pavement may be due to either densification or shear deformation. Densification, or further compaction by traffic, can be reduced by ensuring good compaction during construction. Shear deformation occurs when one or more pavement layers lack bearing capacity. Vertical pressure in unstable layers can be reduced by using stiffer mixes resulting from better compaction. Bell et al. (1984) found a two-fold increase in the estimated permanent deformation lives of a pavement when reducing the void content from eight to four percent (see Table 2.2).

## MIXTURE DESIGN PROCEDURES

### Hveem

The basic philosophy of the Hveem method of mix design is summarized by Roberts et al.(1996) in citing Vallerga and Lovering (1985):

1. It should provide sufficient asphalt cement for aggregate absorption and to produce an optimum film content of asphalt cement on the aggregate.
2. It should produce a compacted aggregate-asphalt cement mixture with sufficient stability to resist traffic.
3. It should contain enough asphalt cement for durability from weathering including the effects of oxidation and moisture susceptibility.

In short, the Hveem method of mix design attempts to maximize durability by selecting the highest asphalt content while still exceeding the minimum stability requirements. The Hveem method has two primary advantages. First, the kneading action of laboratory densification (achieved by a rotating ram having about ¼ the contact area of the 101.6mm (4") diameter mold) simulates the densification characteristics of hot mix asphalt compacted in the field. Second, Hveem stability is a direct measurement of the internal friction component of shear strength because it measures the ability of a test specimen to resist lateral displacement from application of a vertical load. However, the Hveem compactor is somewhat expensive, large, and not very portable. Furthermore, the important mixture volumetric properties described above are not routinely determined as part of the Hveem procedure.

The Hveem method uses the oil soak and Centrifuge Kerosene Equivalent (CKE) tests to aid in determining fine and coarse aggregate absorption for use in estimating the initial asphalt requirements of the mix. Once the initial asphalt content (IAC) is determined, test specimens are prepared containing the IAC, 0.5% and 1.0% above the IAC and 0.5% below the IAC. Compacted samples are put through stabilometer and cohesiometer tests to measure stiffness, a swell test to measure the mix's resistance to moisture, and a density-voids analysis. The optimum asphalt content is determined via a convoluted process involving a highly complex chart requiring several inputs and correction factors.

**Marshall**

A primary advantage of the Marshall method is the attention given to density and voids properties of asphalt mixtures. This analysis ensures the proper volumetric proportions of mixture materials for achieving a durable hot mix asphalt. Additionally, the required equipment is inexpensive and portable thereby lending itself to quality control operations. The Marshall hammer used in the Marshall method is repeatedly dropped onto a sample a prescribed number of times dependent on the estimated traffic level. However, without a kneading action imparting the horizontal shear forces created by rollers, the Marshall hammer does not simulate mixture densification as it occurs in the field. Furthermore, the high variability of results and limited ability to simulate field conditions (temperature, load rate, tire pressures, etc.) of Marshall stability does not adequately estimate the shear strength of hot mix asphalt (Brown et al., 1996). These two situations make it difficult to ensure rutting resistance of the designed mixture (Asphalt Institute 1996).

The two principle features of the Marshall method of mix design are a density-voids analysis and a stability-flow test of the compacted test specimens. The stability of the test specimens is the maximum load resistance in Newtons (lb.) that the standard test specimen will develop at 60°C (140°F). The flow value is the total movement or strain, in units of 0.25 mm (1/100 in), occurring in the specimen between no load and maximum load during the stability test (Asphalt Institute 1989). After determination of an optimum asphalt content, the density-voids analyses and the stability-flow tests are completed on five sets of three samples containing the optimum content, and 0.5% and 1.0% above and below optimum.

In the Marshall method, the mix is compacted using a 101.6 mm (4 in.) diameter by 75 mm (3 in.) high mold and a 4.5 kg (10 lb.) compaction hammer constructed to obtain a 457 mm (18 in.) drop height. Depending on design traffic load, the weight is dropped from its 457 mm height 35 times (light traffic), 50 times (medium traffic) or 75 times (heavy traffic). The mold is flipped and the same number of blows are repeated.

Brown (1984) found that the advent of the mechanical Marshall hammer actually decreased the effectiveness of Marshall compaction in simulating field compaction. Prior to the advent of mechanical compactors, the top of the hammer was held with one hand while the hammer was raised and dropped with the other. The inability to keep the hammer perfectly vertical resulted in a kneading action. Guides on mechanical hammers reduce the kneading action resulting in substantially different laboratory densities (Brown 1984). The Marshall compactor is effective in achieving densification from grain fracturing and particle layer distortion but without a kneading action, densification through particle reorientation is minimal. On examining density-voids relationships of airfield pavements in Kuwait, Bissada (1984) found that even the 75-blow Marshall compaction effort was inadequate as a realistic standard for predicting future densification under traffic. The characteristics of Marshall compacted specimens were not necessarily representative of their lifetime service performance.

**Superpave**

The Strategic Highway Research Program (SHRP) spent five years developing a new mix design methodology, named Superior Performing Pavements, or Superpave. Superpave differed from the Marshall and Hveem methods in several ways: it uses a new "Performance Grade" system for grading asphalt cement; it uses consensus properties for aggregate selection; and it contains new mix design and mixture analysis procedures (Roberts et al. 1996). Superpave is considered a performance-based system because the mixture tests and analyses have direct relationships to field performance (Asphalt Institute 1996).

Traditional grading of asphalts, such as penetration or viscosity graded asphalts, were based on physical properties at standard temperatures. However, such grading systems have two important shortcomings. First, their empirical nature limits their applicability beyond those conditions in which it was developed. A second limitation of previous grading systems is the lack of performance testing over the same temperature range the asphalt will likely see in the field. Superpave's performance graded asphalt system differs from previous grading systems in that the tests measure physical properties that can be directly related to field performance by engineering principles. Another unique feature of the Superpave binder specification system is that instead of performing a test at a constant temperature and varying the specified value, the specified value is constant and the temperature at which this value must be achieved is varied (Asphalt Institute, 1996). The result is an identification system comprised of two numbers: the high temperature grade and the low temperature. For example, a PG 52-34 asphalt binder must posses adequate physical properties at the high temperature, 52°C (125.6°F), and at the low temperature, -34°C (-29.2°F).

Another new feature of the Superpave mix design system is the concept of a restricted zone in the aggregate gradation. The purpose of the restricted zone is to help ensure that too much rounded, natural sand is not used in the mixture and to help ensure that the minimum VMA requirement is achieved (Brown et al., 1996). For blends with nominal sizes 25 mm (1 in.) and greater, the restricted zone boundaries are placed on the 4.75 mm (No. 4), 2.36 mm (No. 8), 1.18 mm (No. 16), 0.60 mm (No. 30), and 0.30 mm (No. 50) sieve sizes. For blends with nominal maximum aggregate sizes of 19 mm (3/4 in.) and less, the 4.75 mm (No. 4) sieve limits are omitted. It is important to note, however, that the restricted zone is just a guide. It is possible to use aggregate blends that pass through the restricted zone that still function satisfactorily. The Superpave system also uses upper and lower control points on the 0.075 mm (No. 200), 2.36 mm (No. 8), and the nominal sieve size of the blend. Additionally, a lower control limit is placed on the sieve size one size lower than the nominal size. Control and restricted zone limits for all nominal maximum aggregate sizes can be found in sources such as the Asphalt Institutes Superpave Series No. 2 manual.

Recognizing the importance of volumetric proportioning, Superpave incorporated aggregate criteria directly into its design procedures. Superpave has two forms of aggregate criteria: consensus properties (aggregate angularity, flat and elongated particles, and sand equivalent or clay content) and source properties (toughness, soundness and deleterious materials). Following is the rationale behind determining the aggregate properties and the test procedures used to determine the properties as given by the Asphalt Institute's Superpave Series No. 2 (SP-2) manual (1996). A complete listing of the minimum required values for the following consensus property tests can be found in the SP-2 manual.

Fine aggregate angularity (FAA) testing is done to ensure a high degree of internal friction and rutting resistance. FAA is defined by the percent of air voids in loosely compacted aggregate smaller than the 2.36 mm (No. 8) sieve. The procedure for FAA testing is outlined in AASHTO TP 33, "*Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, & Grading)*. A sample of fine washed aggregate is poured into a small, calibrated cylinder through a standard funnel. By measuring the mass of fine aggregate in the filled cylinder of known volume, the void content can be calculated as the difference between the cylinder volume and fine aggregate volume collected in the cylinder. Superpave requires a minimum FAA value of 40 for use in mixes placed less than 100 (4 in.) from the surface.

Coarse aggregate angularity (fractured faces), ensures a high degree of aggregate internal friction and rutting resistance. It is defined as the percent by weight of aggregate larger than the 4.75 mm (No. 4) sieve with one or more fractured faces. The procedure for determining coarse aggregate angularity is given in Pennsylvania DOT's Test Method No. 621, "*Determining the Percentage of Crushed Fragments in Gravel.*" The value is typically expressed as the percent with one or more fractured faces over the percent with two or more fractured faces. Superpave minimum CAA requirements range from 55/(nonspecified) for low volume roads to 100/100 for high volume roads.

Flat and elongated coarse aggregate particles are undesirable because they have a tendency to break during construction and under traffic. The fracturing of aggregate is a concern because it can reduce mixture stability and in extreme situations may actually make the gradation finer affecting the optimum asphalt content. The flat and elongated coarse aggregate property is expressed as the percentage by mass of coarse aggregate having a maximum to minimum dimension ratio greater than five to one. It is determined according to ASTM D4791, "*Flat or Elongated Particles in Coarse Aggregate*" on particles larger than 4.75 mm (0.187 in.). Superpave does not limit the percent of flat and elongated particles for low-volume mix designs, but limits their use to ten percent for all other design levels.

The sand equivalency test is a measure of the clay content in the fraction of the fine aggregate smaller than the 4.75 mm (No. 4) sieve. Sand equivalency is determined by the method in AASHTO T176, "*Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*" (ASTM D2419). In the sand equivalency test, a sample of fine aggregate is mixed with a flocculating solution in a graduated cylinder and agitated to loosen the clayey fines and force them into suspension above the granular aggregate. After a settling period, the cylinder heights of the suspended clay and settled sand are measured. The sand equivalent value is the ratio of sand to clay height readings. Minimum Superpave requirements range from 40 percent for low volume roads to 50 percent for high volume.

Samples are compacted in the Superpave gyratory compactor (SGC) and the asphalt content is selected on the basis of volumetric design requirements (the goal being 4% air voids). In its Superpave Series-2 (SP-2) Manual, the Asphalt Institute (1996) identifies several goals of the SHRP efforts in designing the SGC:

- realistically compact mix specimens to densities achieved under actual pavement climate and loading conditions;
- accommodate large aggregate sizes
- measure compactability so potential tender mix behavior could be identified; and
- portable enough for use in mixing facility quality control operations.

The loading ram on an SGC produces a constant 600 kPa (87 psi) vertical compaction pressure on a sample contained in a 150-mm (6 in.) diameter mold (which can accommodate mixes having up to 50-mm (2 in.) maximum size aggregate). The base of the SGC rotates at a constant rate of 30 revolutions per minute with the mold positioned at a 1.25-degree compaction angle. Density can be estimated at any time during the compaction process because the position of the ram is continually recorded as it compacts the specimen (the mass of the mix inside the mold and the mold's diameter are constant). The 1.25°

compaction angle coupled with the revolving base enables the SGC to impart a kneading action on the specimen much like it would undergo in the field. The kneading action enables further densification of the specimen through rearrangement of the aggregate particles.

Superpave mixes are designed at a specific level of compactive effort—the number of gyrations necessary, called N-design ($N_{des}$), to compact the mixture to 4% air voids. $N_{des}$ is a function of climate and traffic levels. Climate is represented by the average design high air temperature and traffic level is represented by the design ESALs (equivalent 80 kN (18,000 lb.) single axle loads). The range of values for $N_{des}$ is show in Table 2.3. The two other values shown in Table 3, $N_{ini}$ and $N_{max}$, also play important roles in the Superpave design process. $N_{ini}$ (N-initial) is considered a measure of mixture compactibility. At $N_{ini}$ gyrations the density of the sample must be greater than 89% of the maximum density. Mixes that compact too quickly (less than 11% air voids at $N_{ini}$) will probably be tender and unstable. $N_{max}$ (N-maximum) is a possible measure of a mix's susceptibility to rutting. The density at $N_{max}$ must be less than 98%. Mixes that compact to greater than 98% air voids at $N_{max}$ may exhibit premature or excessive rutting.

Table 2.3 Superpave Design Gyratory Compactive Effort (Asphalt Institute 1996)

| Design ESALs (millions) | Average Design High Air Temperature | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | <39°C | | | 39 - 40°C | | | 41 – 42°C | | | 43 - 44°C | | |
| | $N_{ini}$ | $N_{des}$ | $N_{max}$ | $N_{ini}$ | $N_{des}$ | $N_{max}$ | $N_{ini}$ | $N_{des}$ | $N_{max}$ | $N_{ini}$ | $N_{des}$ | $N_{max}$ |
| < 0.3 | 7 | 68 | 104 | 7 | 74 | 114 | 7 | 78 | 121 | 7 | 82 | 127 |
| 0.3 - 1 | 7 | 76 | 117 | 7 | 83 | 129 | 7 | 88 | 138 | 8 | 93 | 146 |
| 1 - 3 | 7 | 86 | 134 | 8 | 95 | 150 | 8 | 100 | 158 | 8 | 105 | 167 |
| 3 - 10 | 8 | 96 | 152 | 8 | 106 | 169 | 8 | 113 | 181 | 9 | 119 | 192 |
| 10 - 30 | 8 | 109 | 174 | 9 | 121 | 195 | 9 | 128 | 208 | 9 | 135 | 220 |
| 30 - 100 | 9 | 126 | 204 | 9 | 139 | 228 | 9 | 146 | 240 | 10 | 153 | 253 |
| > 100 | 9 | 143 | 235 | 10 | 158 | 262 | 10 | 165 | 275 | 10 | 172 | 288 |

## USE IN QUALITY CONTROL

A key part of any mixture design system is its ease and reliability when used in the construction process as part of production quality control. Roberts et al. (1996) cite the Federal Highway Administration (FHWA) Demonstration Project No. 74's clear indication that significant differences exist between the volumetric properties of the laboratory designed and plant produced mixtures. Consequently, production quality control is performed by the contractor (typically in on-site laboratories) to ensure the plant is performing as anticipated, and by the owner (typically in mobile laboratories) to ensure production of a consistent, quality product. The first step in production quality control consists of periodic sampling of the material from either behind the paver (preferred) or from the bed of a hauling truck. The sample is then taken to the lab where it is compacted and its volumetric properties are determined. The values are then used to ensure mix production remains within set control limits, and to look for trends signifying the production is out of control (unacceptably large variations) and/or tending towards exceeding a control limit. Without production quality control, there is no means of verifying the product is indeed the consistent, high quality product desired.

When first instituted, the large size and expense of Hveem compactors made efficient production quality control difficult. Furthermore, the absence of routine volumetric property determination in the Hveem method exacerbated problems when volumetric analyses became the primary means of production quality control. The smaller, less costly Marshall hammer, however, was much more suited to on-site laboratories. This situation was acceptable when the majority of mixes were designed using the Marshall method. However, the increasing use of Superpave in the design of asphalt mixtures has brought with it an important question in the quality control process: Can a Marshall compactor (still found in most on-site laboratories) be used to perform production quality control of a Superpave job? D'Angelo et al. (1995) conducted a study to determine whether a Marshall hammer could be used to adequately perform quality control on a Superpave mix and vice-versa. The study examined five different mixes from five different plants by compacting each mix with both a mechanical Marshall hammer and a Superpave Gyratory Compactor. Table 2.4 summarizes the design and compaction methods used in the study:

Table 2.4 Summary of Design and Compaction Methods (D'Angelo et al. 1995)

| Study Number | Design Method | Compaction Effort | Control Compactor | Compaction Effort |
|---|---|---|---|---|
| # 539 | Superpave Level 1 | SGC 150x115mm $N_d$=100 $N_m$=158 | 6-in. (152mm) S. Marshall | 112 blows/side |
| # 540 | 6-in. (152-mm) S. Marshall | 112 blows/side | SGC | $N_d$=100 $N_m$=158 |
| #641 | 4-in. (102-mm) S. Marshall | 50 blows/side | SGC | $N_d$=126 $N_m$=204 |
| # 9401A | 4-in. (102-mm) S. Marshall | 75 blows/side | SGC | $N_d$=109 $N_m$=174 |
| # 9407A | Superpave Level 1 | SGC 150x115mm $N_d$=100 $N_m$=158 | 4-in. (102mm) S. Marshall | 50 blows/side |

The volumetric properties of the mixtures were evaluated to determine if the compaction devices were interchangeable or if the results were dependent on the compaction device used. D'Angelo et al. concluded that when evaluating voids in the total mix (VTM) as the control criterion, the two compactors were interchangeable. Voids in the mineral aggregate (VMA), however, is actually a better criterion to evaluate quality control because it provides a better indication of the aggregate structure within the mix. When using VMA as the criterion, D'Angelo et al. found that the two compactor were not interchangeable.

In two of the mixes, where the SGC indicated a continued increase in VMA with increasing asphalt content, the use of the Marshall hammer resulted in a decrease in VMA.

The SGC indicates the additional binder has filled the void space between the particles forcing them apart. With the Marshall hammer, the additional binder lubricated the aggregate allowing the hammer to compact the mixture more densely. The results clearly indicate that when a mix is designed using Superpave, an SGC must be used for production quality control.

## RUGGEDNESS EVALUATIONS

### Gyratory Compactors

The Marshall and Hveem methods of mix design were developed over 50 years ago. Their strengths and shortcomings are well documented, but Superpave is still relatively new. Its reaction to variabilities in materials and conditions are not well documented. McGennis et al. (1997), in cooperation with the FHWA expert task group, conducted a ruggedness test of the American Association of State Highway and Transportation Officials (AASHTO) Test Method TP4 to evaluate the extent to which variations in test parameters cause variations in test results. AASHTO TP4 is the provisional standard governing the preparation of test specimens with the Superpave Gyratory Compactor. The experiment was conducted using two SGCs that FHWA experiments determined were substantially equivalent: the Pine and Troxler SGCs (D'Angelo, 1995). Table 2.5 shows the seven primary factors and their levels of variation evaluated in the experiment. Table 2.6 lists the eight combinations of variables used in the experiment.

Table 2.5 Main Factors Evaluated in Ruggedness Experiment (McGennis et al. 1997)

| Factor | Levels |
|---|---|
| Angle of Gyration, degrees | Low Range (1.22 to 1.24) and High Range (1.26 to 1.28) |
| Mold Loading Procedure | Transfer Bowl Method and Direct Loading Method |
| Compaction Pressure, kPa | 582 and 618 |
| Precompaction | None and 10 thrusts with Standard Rod |
| Compaction Temperature, °C | @0.250 Pa-s viscosity and @ 0.310 Pa-s viscosity |
| Specimen Height, mm | Low (around 110mm) and High (around 120 mm) |
| Aging Period @ 135°C, hrs | 3.5 and 4 |

Table 2.6 Variable Combinations used in Ruggedness Experiment (McGennis et al. 1997)

| | Combination | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Angle of Gyration, degrees | 1.23 | 1.23 | 1.23 | 1.23 | 1.27 | 1.27 | 1.27 | 1.27 |
| Mold Loading Procedure | TB | TB | DL | DL | TB | TB | DL | DL |
| Compaction Pressure, kPa | 618 | 582 | 618 | 582 | 618 | 582 | 618 | 582 |
| Precompaction | Y | Y | N | N | N | N | Y | Y |
| Compaction Temperature, °C | H | L | H | L | L | H | L | H |
| Specimen Height, mm | L | H | H | L | L | H | H | L |
| Aging Period @ 135°C, hrs | 4.0 | 3.5 | 3.5 | 4.0 | 3.5 | 4.0 | 4.0 | 3.5 |

The nominal angle of gyration in AASHTO TP 4 is 1.25° with an allowable tolerance of 0.02°. The tolerance was established by FHWA because several experiments showed density was profoundly affected by small changes in angle. One study on a project in Arizona determined that a 0.25° change in angle of gyration resulted in a four percent change in void content. However, across the 0.04° range of compaction angles evaluated, the trend toward an increase in density was not significant. Less than one percent of the variation was explained by compaction angle.

Although AASHTO TP4 vaguely informs the operator to "place the mixture in the mold in one lift," experience by the Colorado and Texas DOTs has shown that the method of mold loading has a significant influence on specimen density. The experiences of McGennis et al. (1997) suggested two extremes of mold loading: loading the bowl with a specially designed "gyro loader" transfer bowl; and using a scoop to load the mold directly from the aging pan. Results of this experiment indicate the mold loading procedure does not have a clear, consistent influence on SGC test specimens.

AASHTO TP4 requires a nominal compactive pressure of 600 kPa (87 psi). The allowable three percent tolerance results in test pressures of 582 (84.4 psi) and 618 kPa (89.6 psi). Results indicate a significant difference in density between the two pressures. However, pressure tolerance is not significant since SGCs have transducers enabling operators to set the pressure at exactly 600 kPa (87 psi).

Although TP4 does not require precompaction (the rodding of the mixture prior to compaction), most previous mix design methods such as the Marshall and Hveem methods have required it. Consequently, it is very likely SGC operators would precompact the mix out of habit. Experience has shown it can take as many as 20 gyrations for the compaction pressure to stabilize at 600 kPa (87 psi). It was hypothesized precompaction would enable quicker pressure stabilization resulting in different measured bulk specific gravity. However, results showed the two extremes (zero and 10 rodding strokes) had no significant effect.

AASHTO TP4 specifies mixtures be compacted within a temperature range that results in a binder viscosity between 0.250 Pa-s (2.5 poise) and 0.310 Pa-s (3.1 poise). For the binder in the McGinnis et al. evaluation, a PG 64-22, the resulting compaction temperatures were 141°C (285.8°F) and 146°C (294.8°F). Results indicated compaction temperatures at the extremes of 141°C (285.8°F) and 146°C (294.8°F) do not have a significant effect.

McGennis et al. (1997) discovered the 100-mm (3.94 in.) nominal specimen height requirement of AASHTO TP4 (Edition 1B, September, 1993), is actually incorrect. Most

SHRP research had been completed on specimens with a 115-mm (4.53 in.) nominal height. Additionally, the required ± 1-mm (0.0394 in.) tolerance is counter-productive as it is extremely difficult to achieve on the initial compaction and may simply be too stringent. Consequently, McGennis et al. chose to use a tolerance level of ±5 (0.197 in.). Results showed a significant variability when the height difference of fine graded mixtures exceeded ±12-mm (0.4724 in.). Coarse mixtures did not exhibit a significant variability with respect to height. McGennis et al. concluded a ±5-mm (0.197 in.) tolerance ensures reasonable variability.

Although TP4 requires four hours of short-term oven aging at 135°C (275°F), required compaction temperatures may sometimes be higher than 135°C (275°F). To achieve compaction temperatures above 135°C (275°F), two ovens are often used. The first oven, set at 135°C (275°F), is used for short-term aging of the mix. The second oven is used to heat the specimen up to the required compaction temperature. Two acceptable procedures exist for achieving the increased temperature: placing the mixture in the second oven for up to the 30 allowable minutes *after* the four hours of short-term aging, or removing the mixture from the first oven such that the increased temperature can be obtained ***within*** the required four hours of short-term aging. Therefore, McGennis et al. used 3.5 and 4.0 hours for the extremes of short-term aging. Results indicated the extremes of the short-term aging protocols had an insignificant effect. However, it is important to note this conclusion was reached based upon only one binder. McGennis et al. advise binders exhibiting rapid aging characteristics may be more susceptible to variations in short term aging times. In summary, McGennis et al. concluded the Superpave Gyratory Compactor is a rugged, dependable system that is not very susceptible to operating variations.

## CONCLUSION

The Marshall and Hveem methods of mix design are proven, 50 year-old design procedures. However, they do have their shortcomings. Their primary material characterization tests (Marshall stability and flow and Hveem stability) are not reliable when conditions are outside those in which the tests were developed (i.e. the continuing increase in axle loads and tire pressures). A hot mix asphalt design procedure that characterizes the mixed based on performance-related fundamental engineering properties is required.

Superpave's gyratory compactor plays an important role in producing laboratory-compacted hot mix asphalt samples that are representative of field compaction. Shear and tensile tests are useless if performed on a laboratory specimen that is not representative of a field specimen. Researchers have concluded that as a gyratory compactor, the SGC does a better job of simulating field compaction because its shearing action simulates the densification through particle reorientation achieved by rollers in the field.

# CHAPTER THREE

# RESEARCH METHODOLOGY

## OVERVIEW

The previous section discussed the importance of compaction, the influence of mix properties on volumetrics, and presented the Superpave method of mix design. This section describes the equipment, materials, and procedures used in the production and analysis of mix specimens. Once determined from the mix design, the optimum asphalt contents for the various mixtures were used throughout the remainder of the project. Samples were created at the optimum asphalt content (for 3 percent compacted air voids) for resilient modulus testing at −18°C, 0°C, 25°C, and 40°C (0°F, 34°F, 77°F, 104°F, respectively) to determine each mixture's susceptibility to temperature variation. Moisture sensitivity was evaluated by comparing the indirect tensile strengths between unconditioned, control samples and vacuum-saturated, conditioned samples.

## MIX DESIGN

### Summary of Laboratory Mixes

Generally speaking, it is economically desirable to use low-cost, locally available materials for roads with low traffic volumes. The fine aggregate (FA - passing the 4.75 mm (No.4) sieve) used for every gradation was a sand from Lakeland, Minnesota. It is readily available at low cost, but has a relatively rounded shape. The coarse aggregate (CA – retained on the 9.5 mm (3/8 in.) and larger sieves) used in the project consisted of aggregate from four different sources: Granite Falls (GF) granite, New Ulm (NU) quartzite, Kasota

(KL) limestone, and Cedar Grove (CG) gravel. Two different gradations, shown in Figure 3.1, were used in the project: a *fine* gradation which ran above the Superpave restricted zone; and a *coarse* gradation which ran below the restricted zone. Additionally, two different asphalt cement grades were evaluated: a PG 52-34, the primary grade for the project, was used in all 8 mixes; a PG 58-40 cement was used in the fine gradations for the New Ulm quartzite and Kasota limestone mixes.

Eight different aggregate gradations (four above, two through and two below the restricted zone) using Granite Falls granite (CA) and Lakeland gravel (FA) were evaluated in the attempt to satisfy the Superpave VMA criteria. None of the eight gradations resulted in a sample compacted to 4% air voids having a VMA above the Superpave minimum requirement of 14% for low-volume roads (300,000<ESALs<1,000,000). In fact, the only time the VMA criterion was satisfied was when the 2.36 mm (No. 8) and 1.18 mm (No. 16) Lakeland aggregate was replaced with a Wisconsin, Dresser basalt aggregate having a greater degree of angularity. Since the purpose of the project, however, is to use economical, locally available aggregate, the Dresser aggregate was not used in this project. Instead, the coarse and fine gradations were chosen on the basis of obtaining the best possible VMA/VFA results using a natural sand aggregate source.

The gradation and aggregate sources used in the project are listed in Table 3.1 for both coarse and fine mixes. The Superpave restricted zone, gradation band, and design gradations are illustrated in Figure 3.1.

Table 3.1. Coarse and Fine Mix Gradations

| Sieve Size (mm) | Percent Passing (*Coarse* Gradation) | Percent Passing (*Fine* Gradation) | Aggregate Source |
|---|---|---|---|
| 19 | 100.0 | 100.0 | |
| 12.5 | 93.2 | 96.1 | GF/NU/KL/CG |
| 9.5 | 66.2 | 83.1 | GF/NU/KL/CG |
| 4.75 | 47.3 | 70.1 | Lakeland Gravel |
| 2.36 | 33.8 | 57.1 | Lakeland Gravel |
| 1.18 | 23 | 44.2 | Lakeland Gravel |
| 0.600 | 16.2 | 31.2 | Lakeland Gravel |
| 0.300 | 12.2 | 18.2 | Lakeland Gravel |
| 0.150 | 8.1 | 7.8 | Lakeland Gravel |
| 0.075 | 4.1 | 3.9 | Lakeland Gravel |
| PAN | 0.0 | 0.0 | Baghouse Fines |

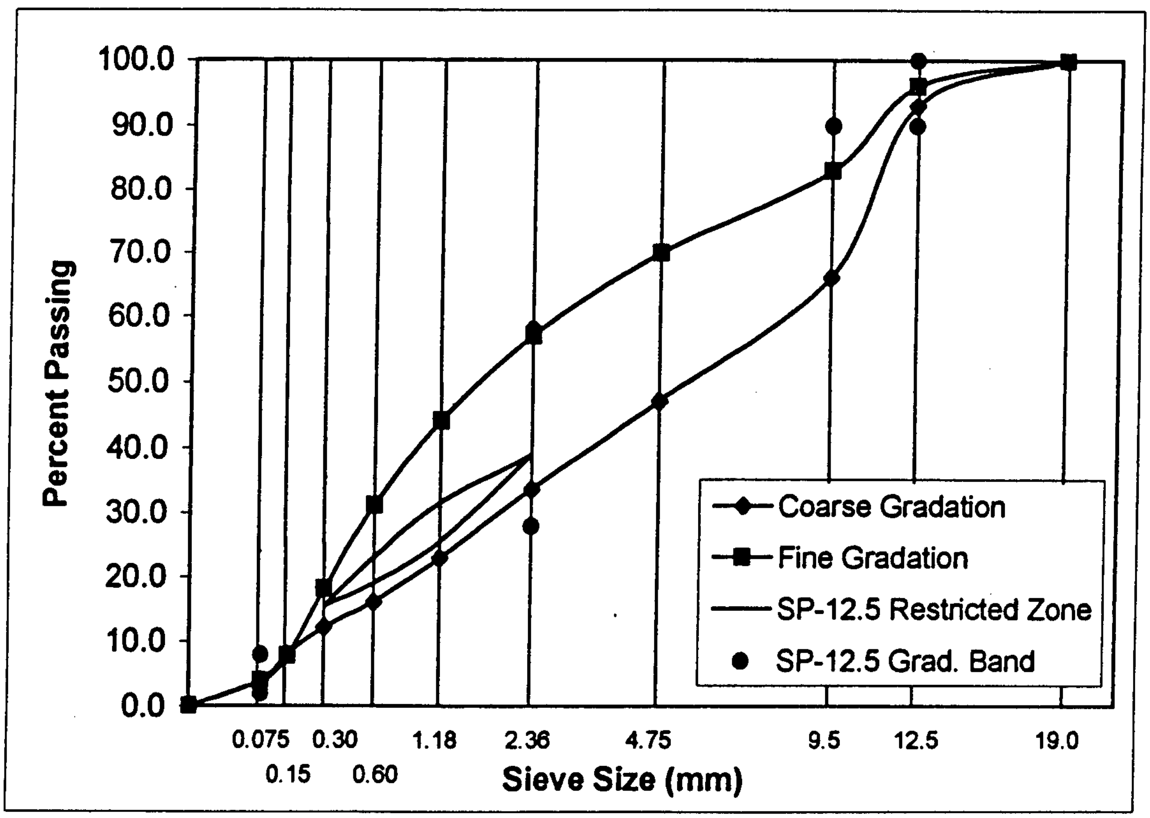


Figure 3.1. Experimental Mix Gradations

## Aggregate Properties

The fine aggregate (FA) used for every gradation was a Lakeland gravel. It is readily available at low cost, but has a relatively low fine aggregate angularity (FAA) of 0.40. The coarse aggregates (CA) are Granite Falls Granite, New Ulm Quartzite, Kasota Limestone, and Cedar Grove Gravel. Tables 3.2 and 3.3 list the aggregate properties for the fine and coarse mixes, respectively.

Table 3.2 Fine Aggregate Properties

| TEST | LAKELAND GRAVEL |
|---|---|
| $G_{sb}$ | 2.602 |
| $G_{sa}$ | 2.770 |
| Water Absorption, % | 2.3 |
| Fine Aggregate Angularity, % | 39.9 |
| Sand Equivalent, % | 48 |

Table 3.3 Coarse Aggregate Properties

| TEST | Granite Falls Granite | New Ulm Quartzite | Kasota Limestone | Cedar Grove Gravel |
|---|---|---|---|---|
| $G_{sb}$ | 2.757 | 2.624 | 2.492 | 2.610 |
| $G_{sa}$ | 2.797 | 2.661 | 2.770 | 2.731 |
| Water Absorption, % | 0.46 | 0.53 | 4.0 | 1.7 |
| Flat/Elongated Particles %, (1:3 Ratio) | 14.0 | 35.0 | 11.1 | 8.2 |
| Fractured Faces %, ($\geq 1$ / $\geq 2$) | 100/100 | 100/100 | 100/100 | 64.7/38.6 |

All fine and coarse aggregate consensus property testing was done in accordance with Superpave specifications. The FAA of the Lakeland aggregate was determined using

AASHTO TP33, "*Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, & Grading—Method A).*" The Sand Equivalency of the Lakeland aggregate was determined using AASHTO T176, "*Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*" (ASTM D2419).

The procedure used to determine the flat/elongated particle percentage of the Granite Falls, New Ulm, Kasota, and Cedar Grove aggregates was ASTM D4791, "*Flat or Elongated Particles in Coarse Aggregate.*" The final aggregate property, coarse aggregate angularity, or fractured faces, was done in accordance with the Pennsylvania DOT's Test Method No. 621, "*Determining the Percentage of Crushed Fragments in Gravel.*"

**Gyratory Compactor**

The compactor used throughout the project was the Brovold gyratory compactor—a Superpave Gyratory Compactor manufactured by Test Quip. The Brovold compactor is considered an Intensive Compaction Tester (ICT)—operating on a "shear compaction" principle. Compaction occurs via two distinct elements: vertical pressure and shear displacement. These two elements combine to encourage the reorientation of aggregate particles—essential for the compaction of any particulate specimen.

A piston pushing down on a plate resting on top the asphalt specimen inside the compaction mold supplies the vertical pressure. The Superpave standard of 600kPa (87 psi) was used throughout the project. The gyratory motion of the compactor creates the necessary shear force. Increasing the angle of the gyration increases the shear force created by the compactor. Superpave guidelines, however, set the gyratory angle at $1.25 \pm 0.02°$. Figure 3.2 illustrates the resulting shear displacement described above.

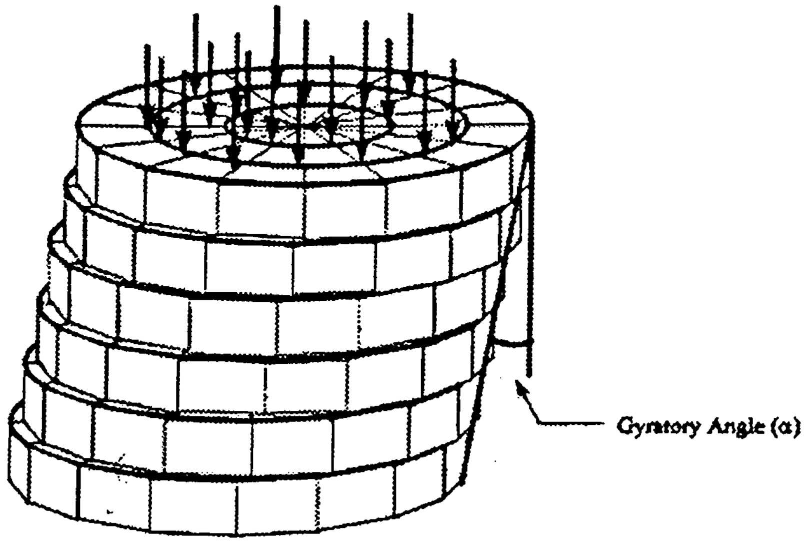


Figure 3.2. Shear Displacement During Gyratory Compaction
(De Sombre, 1998)

The height of the sample is continually recorded by a linear variable displacement transducer (LVDT). The density of the sample at each gyration is calculated using the current height and mass of the sample. The operator is able to control the compaction energy transmitted to the sample by inputting the desired number of gyrations. Superpave specifies the number of gyrations as a function of temperature and anticipated traffic.

**Compaction Procedure**

Prior to mixing, pre-batched, 12,000-gram (26.5 lb.) aggregate samples were placed in a forced-draft oven for a minimum of four hours to ensure adequate drying. Simultaneously, the asphalt binder was pre-heated to the appropriate mixing temperature, 138°C (280°F) for PG 52-34 and 145°C (293°F) for PG 58-40. The aggregate was first poured into a bucket mixer followed by the appropriate amount of asphalt cement. After adequate mixing in the bucket mixer, the mixture was placed in a large pan and mixed by hand to prevent segregation. Each batch was then split into two 4,800-gram (10.6 lb.)

samples for compaction, and two 1,000-gram (2.2 lb.) samples for Theoretical Maximum Specific Gravity testing. Mix design samples were prepared according to the matrix shown in Table 3.4. $P_b$, the initial asphalt content, was determined using the spreadsheet shown in Appendix A.

Table 3.4 Mix Design Matrix

| Aggregate Type | Asphalt Grade | Superpave Level I Mix Design | | | |
|---|---|---|---|---|---|
| | | Asphalt Content | | | |
| | | $P_b$–0.5 | $P_b$ | $P_b$+0.5 | $P_b$–1.0 |
| GFC | PG 52-34 | X | X | X | X |
| GFF | PG 52-34 | X | X | X | X |
| NUC | PG 52-34 | X | X | X | X |
| NUF | PG 52-34 | X | X | X | X |
| KLC | PG 52-34 | X | X | X | X |
| KLF | PG 52-34 | X | X | X | X |
| CGC | PG 52-34 | X | X | X | X |
| CGF | PG 52-34 | X | X | X | X |
| NUF | PG 58-40 | X | X | X | X |
| KLF | PG 58-40 | X | X | X | X |

The samples were compacted using Test Quip's Brovold gyratory compactor. The PG 52-34 samples were compacted at 128°C (262.4°F) . The PG 58-40 samples were compacted at 135°C (275°F) . The required number of gyrations was based on low-volume, level two, traffic: 300,000 to 1,000,000 ESALs. Therefore, $N_{ini}$ = 7, $N_{des}$ = 76, and $N_{max}$ = 117.

## RESILIENT MODULUS

Resilient modulus tests were conducted on all samples to determine the mixtures' susceptibility to temperature changes. The test was conducted in accordance with ASTM D 4123-82 (1987), "*Standard Test Method for Indirect Tension Test for Resilient Modulus of*

*Bituminous Mixtures.*" Samples were typically loaded to a stress level between 5 and 20 percent of indirect tensile strength (measured or estimated prior to conducting resilient modulus tests). Loads were applied in cycles consisting of 0.1 second load and 0.9 second no-load rest. After test completion, the resilient modulus was calculated via the following equation:

$$M_R = P/Ht * (0.27 + \mu) \tag{3.1}$$

Where

$M_R$ = resilient modulus, Pa
P = applied load, Newtons
H = horizontal deformation, mm
t = sample thickness, mm
$\mu$ = Poisson's ratio

Poisson's ration can be calculated as

$$\mu = 3.59\ H/V - .27 \quad \text{(for 100 mm samples), or} \tag{3.2}$$
$$\mu = 4.09\ H/V - .27 \quad \text{(for 150 mm samples)} \tag{3.3}$$

where

$\mu$ = Poisson's ratio
H = horizontal deformation, mm
V = vertical deformation, mm

Poisson's ratio values were assumed as follows (Brown et al., 1996)): 0.25 for 5°C (41°F); 0.35 for 25°C (77°F), or 0.40 for 40°C (104°F).

There is much debate over the applicability of resilient modulus values in the prediction of long-term pavement performance. It was once commonly believed stiffer pavements (those with higher resilient modulus values) had greater resistance to permanent deformation. Roberts et al. (1996) caution that, to date, there is no solid correlation between $M_R$ and rutting. Roberts et al. have concluded, however, $M_R$ at low temperatures is somewhat related to cracking as stiffer mixes (higher $M_R$) at low temperatures tend to crack earlier than more flexible mixtures (lower $M_R$).

For the Superpave project, three 3400-gram (7.5 lb.) samples were made for each of the ten mixes. Each of the samples were tested at both zero and 90-degree orientations. A minimum 2-hour waiting period was maintained between zero and 90-degree testing to provide the samples time to recover from any distortion that might have resulted from the previous test. All 30 samples were tested at –18°C, 0°C, 25°C, and 40°C (0°F, 34°F, 77°F, 104°F, respectively). At each temperature, the samples were placed in temperature controlled environmental chambers for a minimum of 24 hours to ensure equilibrium had been reached at the respective temperature. Isopropyl alcohol was used to remove any ice accumulation from the extensometers. Due to the inherent high variability of resilient modulus testing, samples with suspected erroneous test results were immediately re-tested. Test results were continually examined to protect against inaccurate data resulting from damaged samples.

## MOISTURE SENSITIVITY

The effects of moisture sensitivity can be as minor as the weakening of the bond between the asphalt cement and the aggregate or as drastic as the sudden peeling off of the asphalt so only bare aggregate remains. The more typical scenario is a gradual loss of strength over a period of years resulting in the development of rutting and shoving in the wheel paths. To help protect against moisture damage it is necessary to determine if a mixture is susceptible to water damage in the event of water penetration.

Moisture sensitivity tests were conducted in accordance with ASTM D4867. One set of six specimens for each mixture was compacted to between 6 and 8 percent air voids. Each set was then divided into two subsets of approximate equal void content. One subset was maintained dry while the other subset was partially saturated with water and moisture conditioned. The samples were vacuum saturated to between 55 and 80 percent. After being partially saturated, the conditioned samples were placed in a 60°C water bath for 24 hours. Both subsets were then subjected to the tensile splitting test and loaded with a diametral load until failure. The tensile strength of each subset was determined by equation 3.4.

$$S_t = \frac{2000P}{\pi t D} \text{ (kPa)} \qquad (3.4)$$

where

$S_t$ = tensile strength, kPa
P = maximum load, N
t = specimen height before tensile test, mm
D = specimen diameter

The potential for moisture damage is indicated by the tensile strength ratio (TSR): the ratio of the tensile strength of the wet subset to that of the dry subset. The TSR for each mixture is calculated by equation 3.5.

$$TSR = \frac{S_{tw}}{S_{td}} \times 100 \qquad (3.5)$$

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## RESULTS

### Aggregate Testing

Table 4.1 provides the results for the fine aggregate angularity and sand equivalency tests conducted on the fine aggregate and compares them with the Superpave criteria for low volume roads (< 1,000,000 ESALs). Although easily meeting the Sand Equivalent minimum value, the Lakeland aggregate barely made the 40% minimum fine aggregate angularity value. As discussed in the Mix Design section, the low fine aggregate angularity of the Lakeland aggregate is suspected to be the primary cause of the inability to meet the VMA criterion. Table 4.2 provides the same comparison for the flat/elongated particles and fractured faces tests done on the coarse aggregate. A quick review of Tables 4.2 shows that all four coarse aggregates are acceptable for use in Superpave low-volume mix designs. As is typical with any non-crushed aggregate such as gravels, the Cedar Grove aggregate had a very low fractured faces value—barely meeting the 65% minimum. As will be discussed later in the Resilient Modulus and Moisture Sensitivity sections, however, the low fractured faces percentage of the Cedar Grove aggregate appeared to have no effect on its performance as compared to the other three aggregates evaluated.

Table 4.1 Fine Aggregate Properties

| TEST | LAKELAND SAND | Superpave Criteria ($<10^6$ ESALS) |
|---|---|---|
| Fine Aggregate Angularity, % | 40 | 40 (min) |
| Sand Equivalent, % | 48 | 40 (min) |

Table 4.2 Coarse Aggregate Properties

| TEST | Granite Falls Granite | New Ulm Quartzite | Kasota Limestone | Cedar Grove Gravel | SP Criteria (<$10^6$ ESALS) |
|---|---|---|---|---|---|
| Flat/Elongated Particles %, (1:3 Ratio) | 14 | 35 | 11 | 8 | None |
| Fractured Faces %, (≥ 1 / ≥ 2) | 100/100 | 100/100 | 100/100 | 65/39 | 65/- |

**Mix Design**

Figures 4.1, 4.2, and 4.3 show the air voids versus asphalt content for the coarse, fine and PG 58-40 mixes, respectively. Figures 4.4, 4.5, and 4.6 show the VMA versus asphalt content for the mixes, and VFA versus asphalt content is shown in Figures 4.7, 4.8, and 4.9. Table 4.3 summarizes the data for both three and four percent air voids. As shown in Table 4.3, the VMA criterion is not satisfied by any of the mixes at 4% compacted air voids. Additionally, at 4% voids, five of the ten mixes did not meet the VFA criteria (65%<VFA<78%), while the remaining five had only 66% VFA. Low VMA and VFA may result in low aggregate film thickness which may lead to accelerated aggregate stripping and other related durability problems.

An analysis of the mix design data at 3% air voids shows no significant change in VMA but large increases in VFA. At 3% voids, all 10 mixes satisfy the Superpave VFA criterion. The substantial increase in VFA at 3% air voids should reduce the concern over aggregate film thickness. Therefore, it was determined the target asphalt content for the project would be based on 3% air voids.

As shown in Table 4.4, at 3% air voids, only the fine and coarse Kasota limestone mixes satisfied the Superpave criteria for compacted densities at $N_{ini}$ and $N_{max}$. The remaining fine gradation mixes (including the two PG 58-40 mixes) failed the <89% of maximum density criterion at $N_{ini}$. The remaining coarse gradation mixes did not meet the

$N_{max}$. The implications associated with these observations will be addressed in the Discussions section. All 10 mixes met the Superpave dust proportion criterion of 0.6 to 1.2.

Although neither is significantly higher, the Granite Falls aggregate appeared to have the highest VMA of the four coarse aggregates and the PG 58-40 binder bettered the PG 52-34 binder. Another interesting observation shown in Table 4.4 concerns the optimum asphalt content of the coarse graded Kasota limestone mix. Although, the Kasota limestone has the *highest* water absorption of the four coarse aggregates (reference Table 3.3), it had the *lowest* optimum asphalt content. Although no explanation is known, such a phenomenon is normally the result of either equipment or operator error.

Table 4.3 Summarized Mixed Design Results @ 4% Air Voids*

| Aggregate | AC Content @ 4% Voids | VMA, % (≥14%) | VFA, % (65-78%) | % Gmm @ Nini < 90.5%? | % Gmm @ Nmax < 98%? | Dust Prop b/w 0.6 and 1.2? |
|---|---|---|---|---|---|---|
| GFC | 4.00 | 11.5 | 66 | 88.2 | 97.1 | 1.04 |
| GFF | 4.60 | 11.9 | 66 | 90.8 | 96.7 | 0.87 |
| NUC | 3.95 | 10.4 | 62.5 | 87.6 | 97.1 | 1.04 |
| NUF | 4.65 | 10.8 | 64 | 90.8 | 96.7 | 0.87 |
| KLC | 3.95 | 9.6 | 59 | 88.3 | 97.3 | 1.04 |
| KLF | 4.65 | 10.8 | 64 | 90.9 | 96.8 | 0.87 |
| CGC | 3.90 | 9.75 | 56 | 88.0 | 97.1 | 1.06 |
| CGF | 4.75 | 11.8 | 66 | 90.7 | 96.7 | 0.84 |
| NUF (58-40) | 4.45 | 11.6 | 66 | 90.9 | 96.6 | 0.89 |
| KLF (58-40) | 4.60 | 11.5 | 66 | 90.8 | 96.7 | 0.87 |

*Underlined values do not meet Superpave criteria.

Table 4.4 Summarized Mixed Design Results @ 3% Air Voids*

| Aggregate | AC Content @ 4% Voids | VMA, % (≥13%) | VFA, % (65-78%) | % Gmm @ Nini < 90.5%? | % Gmm @ Nmax < 98%? | Dust Prop b/w 0.6 and 1.2? |
|---|---|---|---|---|---|---|
| GFC | 4.30 | 11.5 | 74 | 90.1 | 98.2 | 0.97 |
| GFF | 4.80 | 12.4 | 74 | 91.6 | 97.6 | 0.84 |
| NUC | 4.95 | 11.3 | 73 | 88.4 | 98.1 | 0.82 |
| NUF | 5.00 | 10.5 | 73 | 91.8 | 97.6 | 0.80 |
| KLC | 4.20 | 9.0 | 70 | 89.0 | 98.1 | 0.97 |
| KLF | 5.20 | 10.8 | 72 | 91.7 | 97.8 | 0.74 |
| CGC | 4.70 | 10.5 | 72 | 88.7 | 98.2 | 0.86 |
| CGF | 5.00 | 11.5 | 74 | 91.5 | 97.5 | 0.80 |
| NUF (58-40) | 4.90 | 11.4 | 74 | 92.0 | 97.7 | 0.82 |
| KLF (58-40) | 4.90 | 11.3 | 74 | 91.9 | 97.7 | 0.82 |

*Underlined values do not meet Superpave criteria.

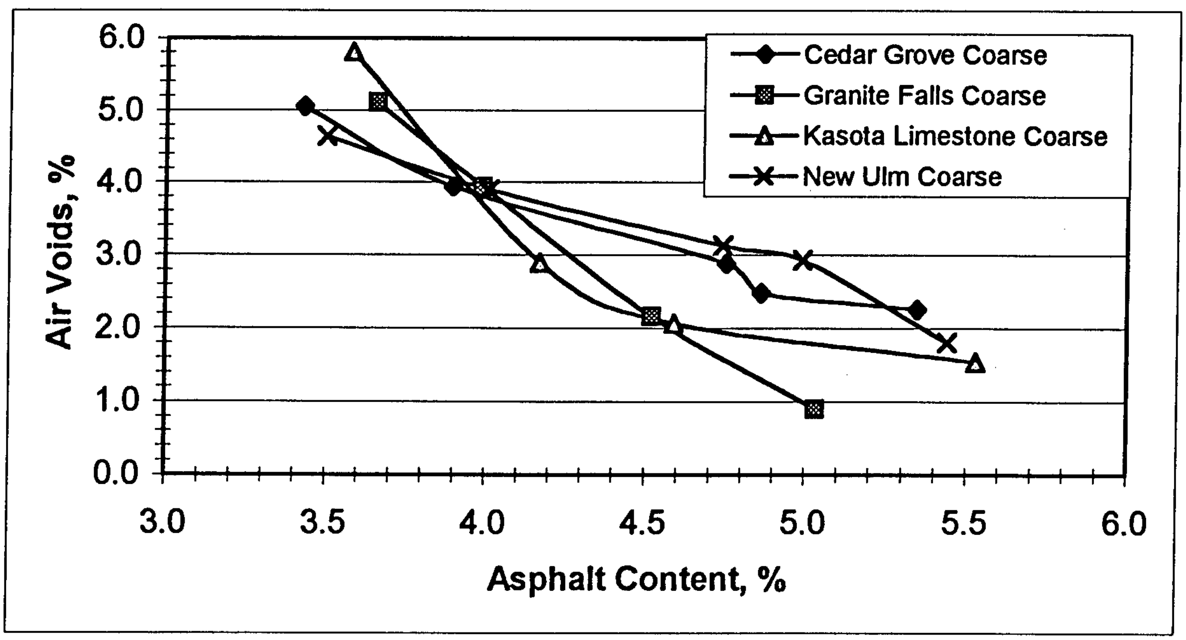


Figure 4.1 Air Voids vs Asphalt Content for Coarse Mixes

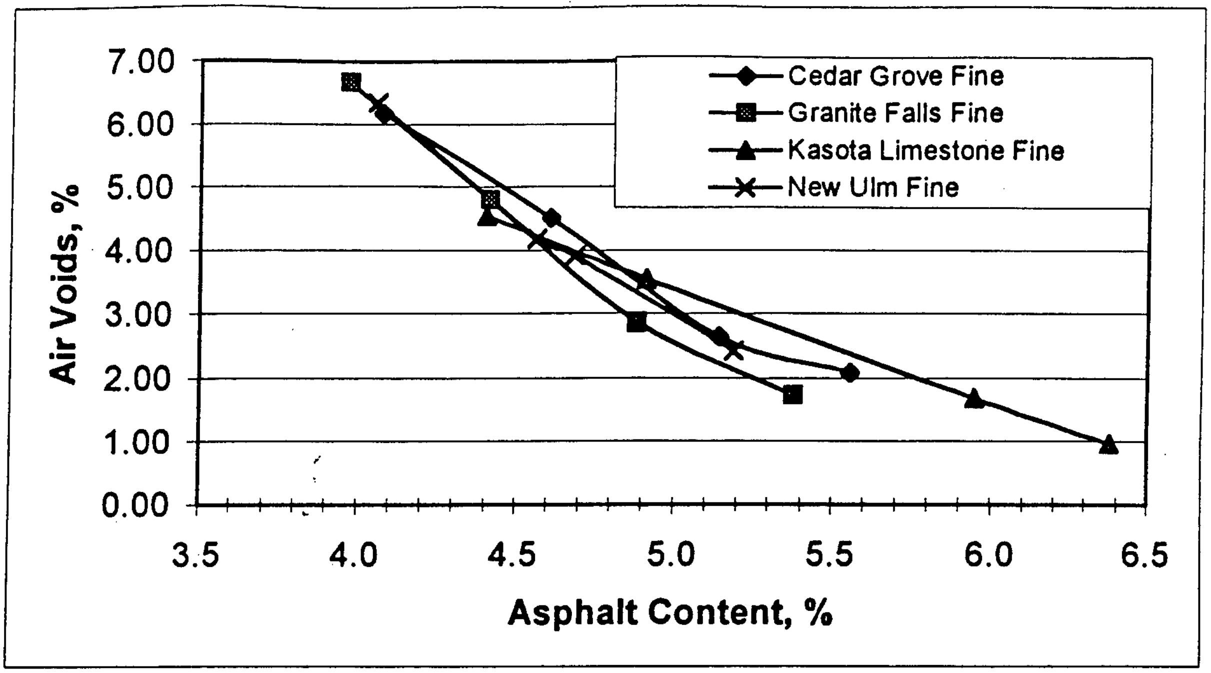


Figure 4.2 Air Voids vs Asphalt Content for Fine Mixes

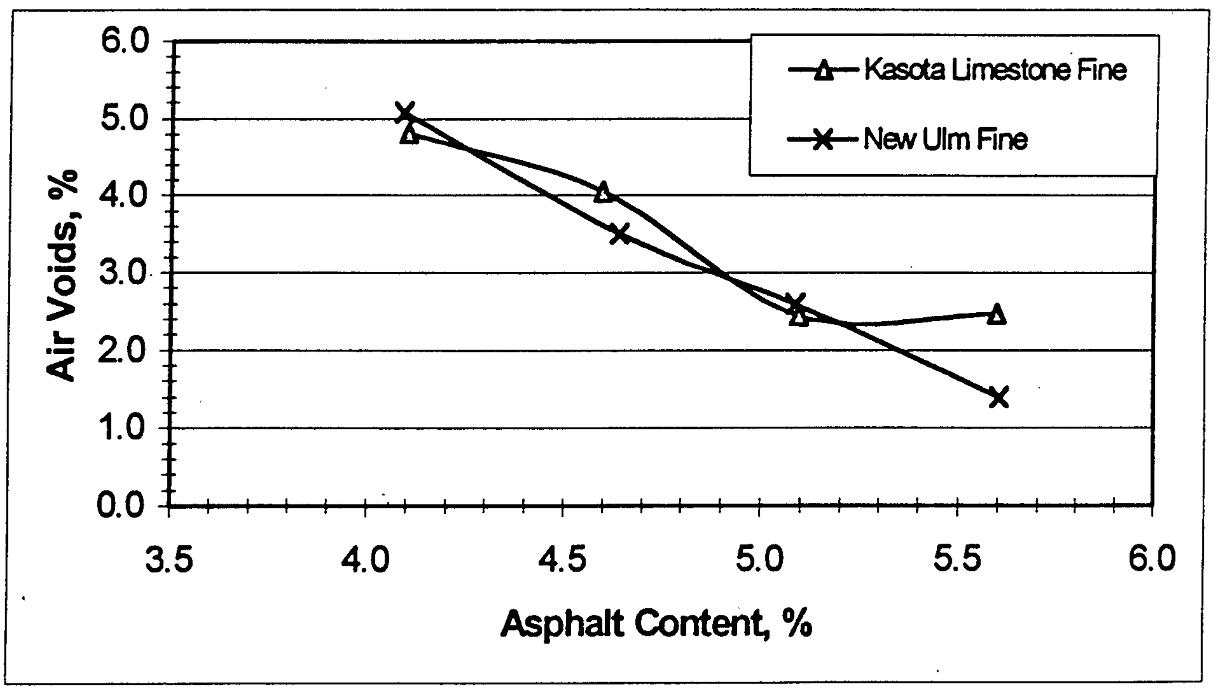


Figure 4.3 Air Voids vs Asphalt Content for PG 58-40 Mixes

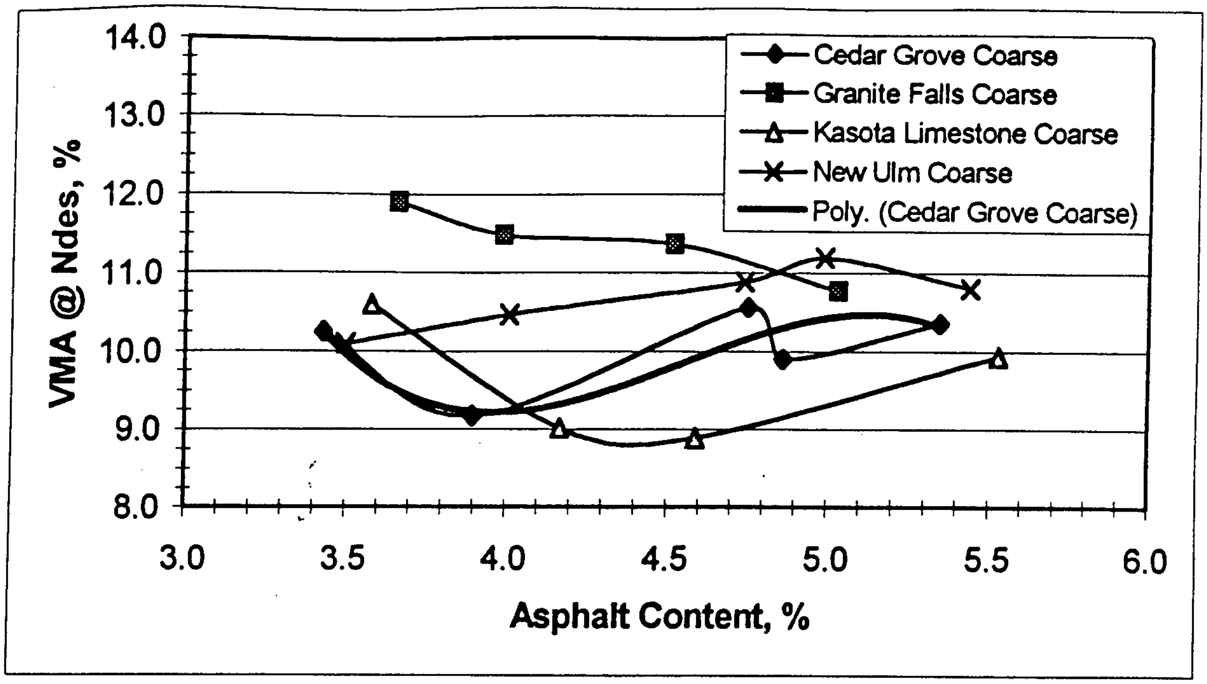


Figure 4.4 VMA @ $N_{des}$ vs Asphalt Content for Coarse Mixes

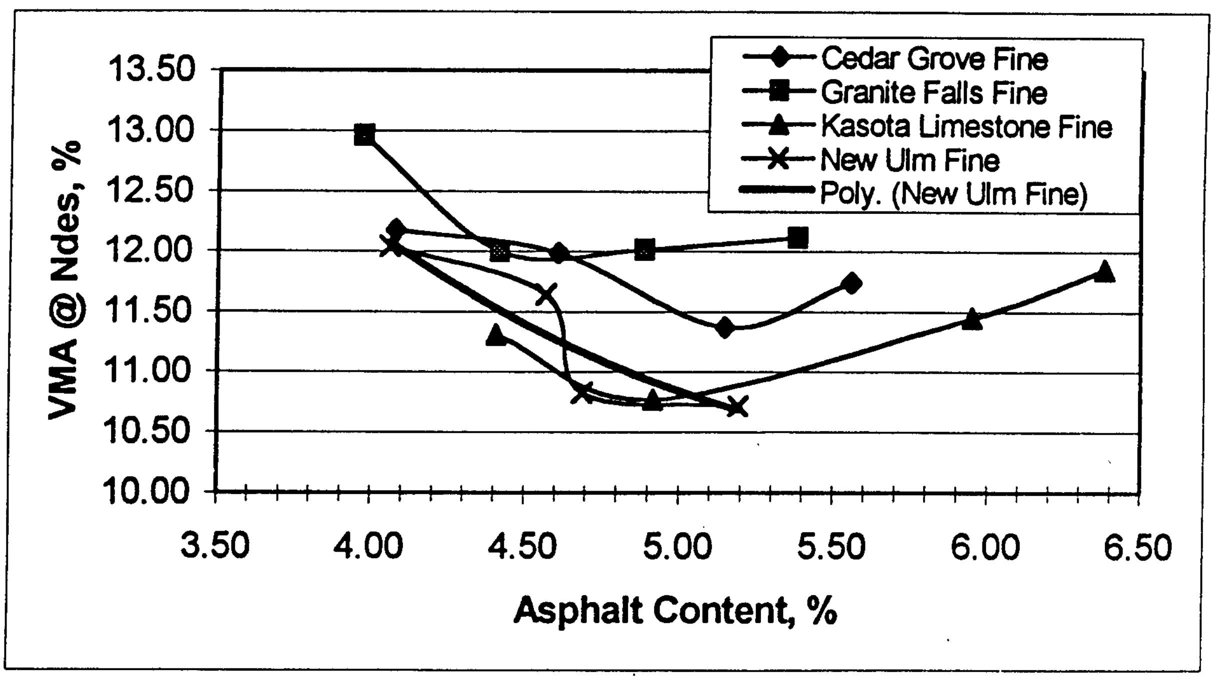


Figure 4.5 VMA @ $N_{des}$ vs Asphalt Content for Fine Mixes

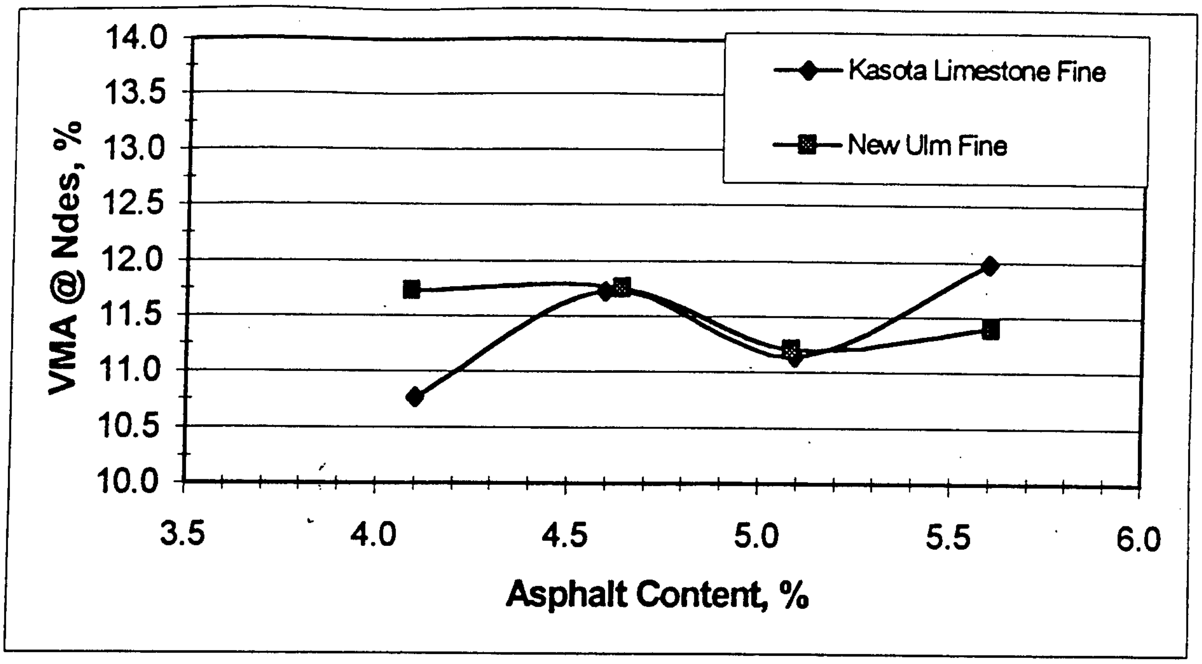


Figure 4.6 VMA @ $N_{des}$ vs Asphalt Content for PG 58-40 Mixes

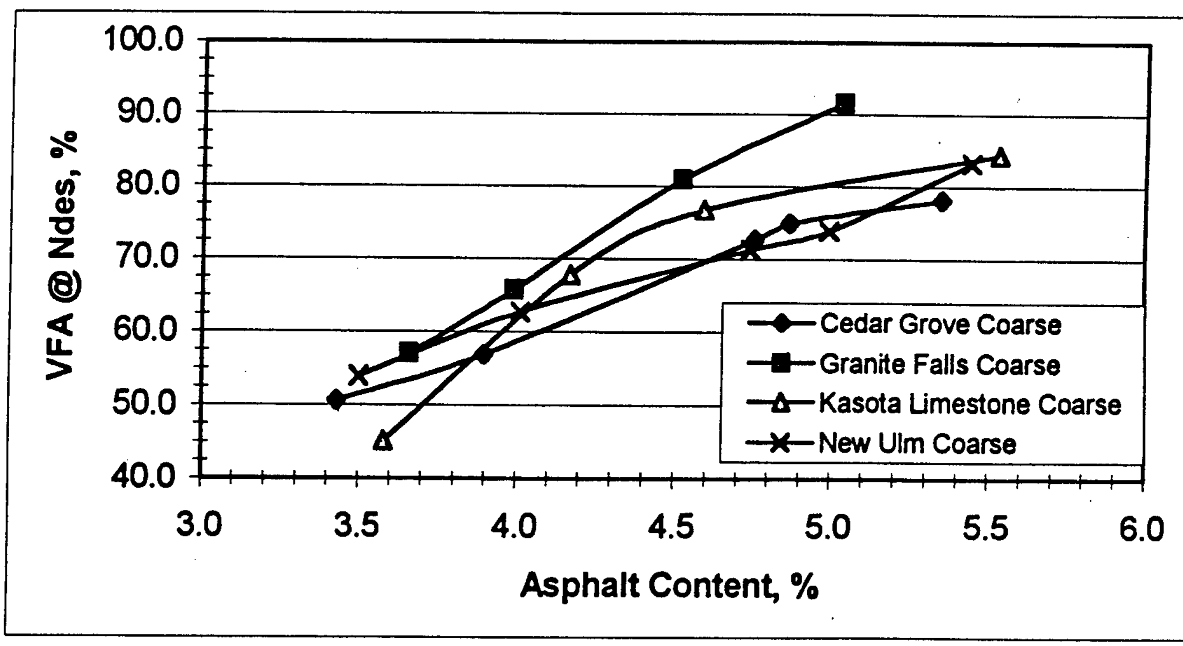


Figure 4.7 VFA @ $N_{des}$ vs Asphalt Content for Coarse Mixes

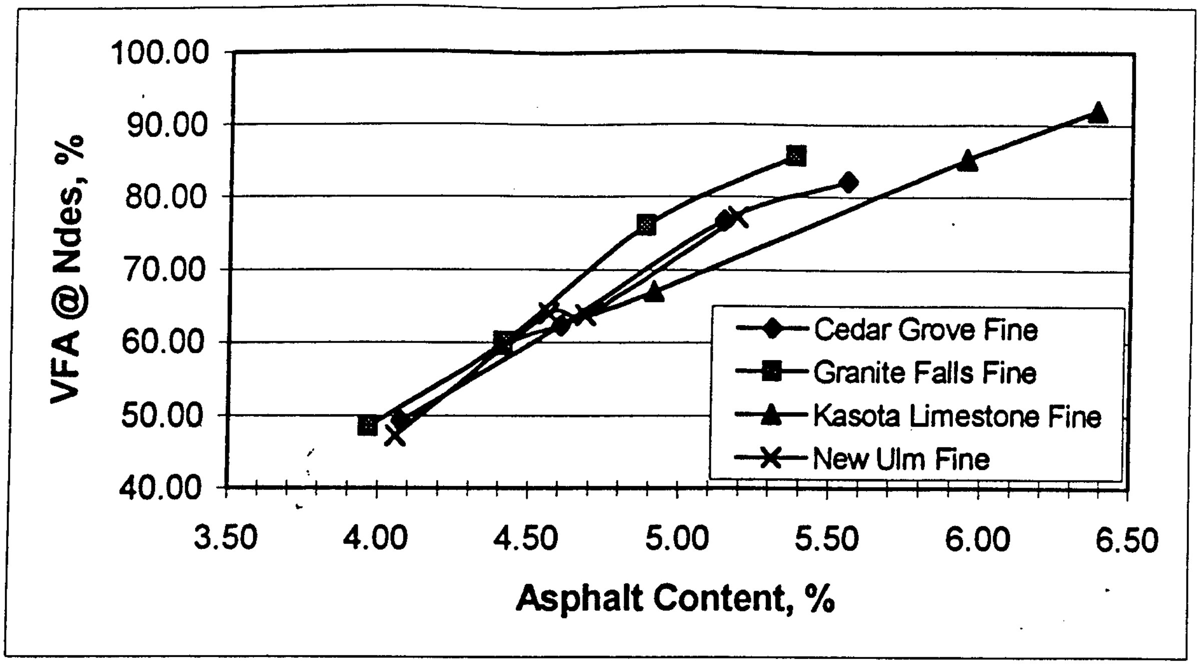


Figure 4.8 VFA @ $N_{des}$ vs Asphalt Content for Fine Mixes

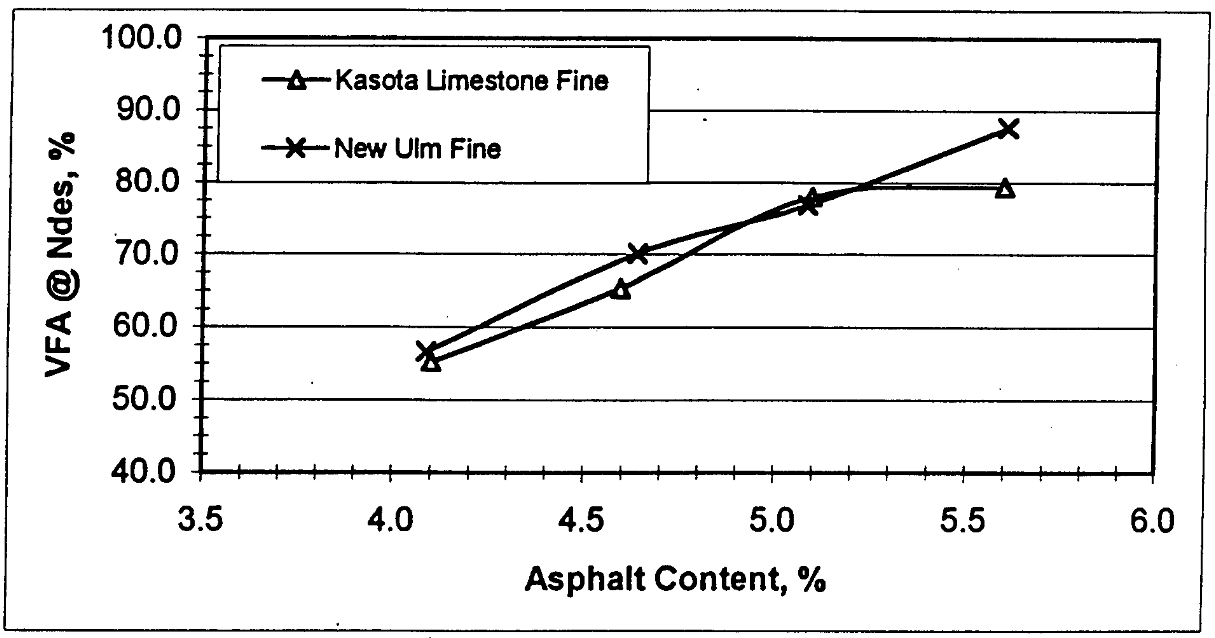


Figure 4.9 VFA @ $N_{des}$ vs Asphalt Content for PG 58-40 Mixes

## Resilient Modulus

Three samples from each mix type were tested in accordance with ASTM D4123. The average values by temperature for each mix type are shown in Table 4.5. The average coefficient of variation (COV) for each mix is also provided in Table 4.5. Complete test results are provided in Appendix B.

Table 4.5 Average Resilient Modulus Test Results

| GRADATION | Test Temperature (Deg) | -18 | | 0 | | 25 | | 40 | |
|---|---|---|---|---|---|---|---|---|---|
| | Freqency = 1.0 hz | Res Mod (KPa) | Coef. of Var. (%) | Res Mod (KPa) | Coef. of Var. (%) | Res Mod (KPa) | Coef. of Var. (%) | Res Mod (KPa) | Coef. of Var. (%) |
| COARSE | Granite Falls Granite | 12204.06 | 17.71 | 9272.99 | 3.06 | 1676.36 | 2.53 | 434.65 | 3.71 |
| | New Ulm Quartzite | 14242.53 | 17.05 | 8159.79 | 5.15 | 1517.05 | 1.83 | 442.33 | 2.69 |
| | Kasota Limestone | 11559.53 | 18.07 | 9579.18 | 3.72 | 2223.58 | 2.08 | 705.41 | 4.84 |
| | Cedar Grove Gravel | 14227.92 | 23.32 | 9178.99 | 3.94 | 1834.52 | 1.74 | 525.78 | 3.50 |
| FINE | Granite Falls Granite | 12326.15 | 20.13 | 9445.77 | 3.60 | 1749.17 | 1.74 | 544.88 | 3.72 |
| | New Ulm Quartzite | 13115.18 | 14.87 | 9429.47 | 4.66 | 1919.89 | 1.55 | 571.13 | 3.25 |
| | Kasota Limestone | 12393.15 | 11.41 | 9356.27 | 4.54 | 1873.67 | 1.68 | 597.56 | 4.17 |
| | Cedar Grove Gravel | 11841.31 | 16.42 | 9324.85 | 4.61 | 1776.77 | 1.95 | 508.20 | 4.79 |
| FINE (58-40) | New Ulm Quartzite | 11796.54 | 10.50 | 5950.43 | 2.78 | 1135.26 | 0.94 | 635.97 | 2.50 |
| | Kasota Limestone | 12392.39 | 10.86 | 5812.05 | 3.68 | 1315.57 | 1.02 | 547.78 | 2.74 |

A comparison of coarse versus fine gradations is illustrated in Figure 4.10. Average values for the four coarse mixes and for the four fine mixes were used to make the comparison shown in Figure 4.10. As shown by Figure 4.10, the two gradations are virtually indistinguishable from one another.

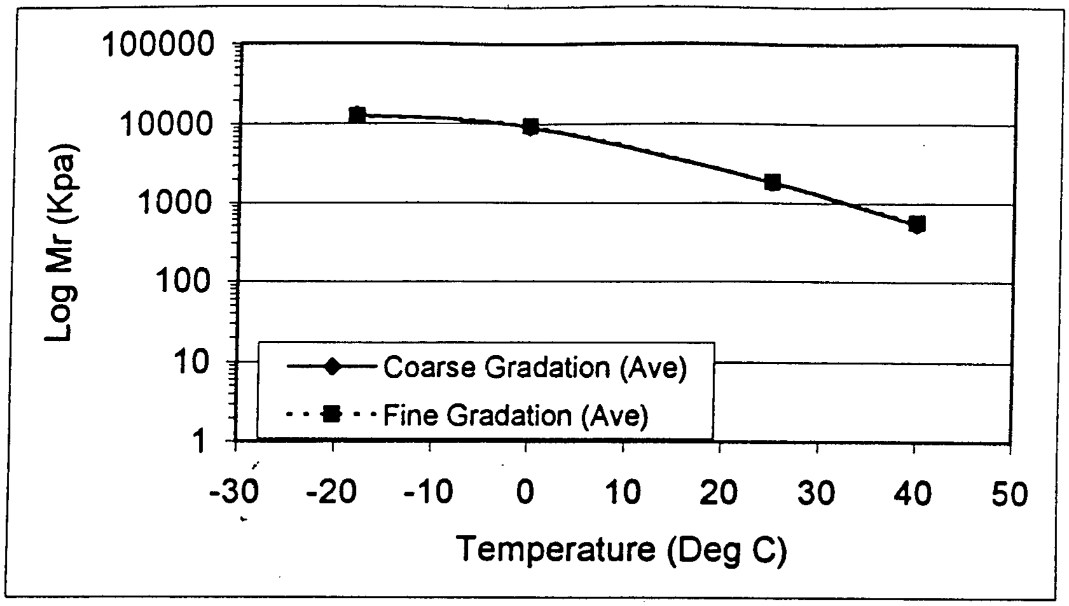


Figure 4.10 Influence of Gradation on Stiffness

The four aggregates (granite, quartzite, limestone, and gravel) are compared in Figure 4.11. Here, the coarse and fine gradations for each aggregate type were averaged together. The Kasota limestone has a slightly higher warm temperature resilient modulus, and the remaining three aggregate types are indistinguishable from one another.

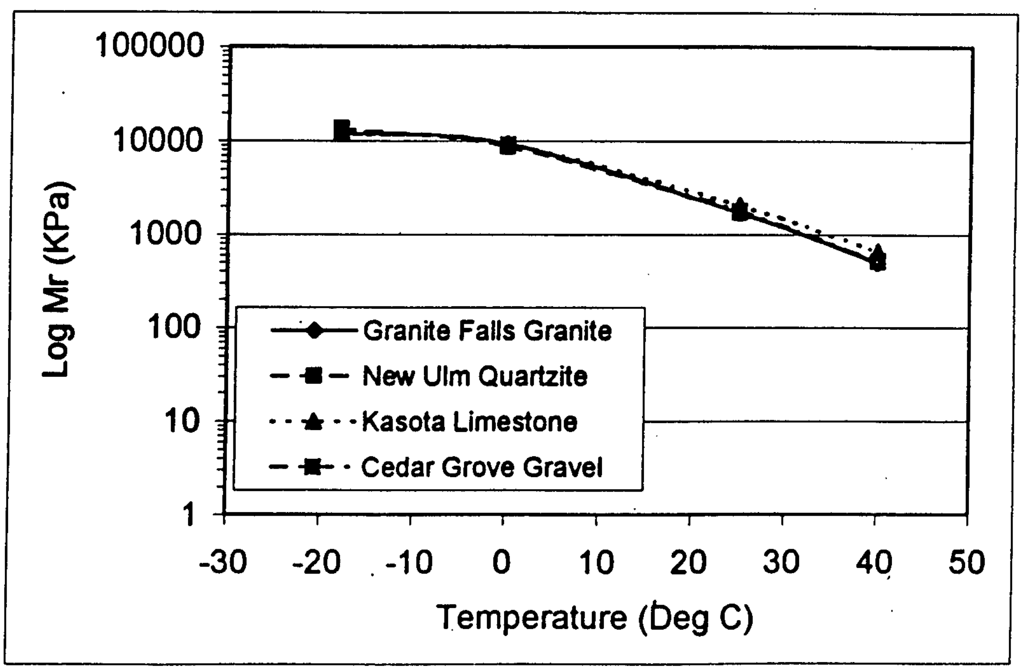


Figure 4.11 Influence of Aggregate on Stiffness

Lastly, the two asphalt grades (PG 52-34 verses PG 58-40) are compared in Figure 4.12. This comparison was made by averaging the New Ulm and Kasota values together for each asphalt grade. The results of the performance grade comparison somewhat surprising. It was expected the two grades would have similar resilient moduli at the moderate temperatures and different moduli at the warmest and coldest temperatures. The purpose of the performance graded asphalt system is to ensure adequate pavement flexibility at cold temperatures to reduce cold temperature cracking and adequate stiffness at high tempures to reduce permanent deforemation. Therefore, had the samples been tested at temperature extremes closer to the PG 58-40 rating (i.e. -40°C (-40°F) and 58°C (136°F)), it is expected the PG 58-40 would have had a lower resilient modulus at the cold extreme and a higher resient moduls at the hot extreme than the PG 52-34.

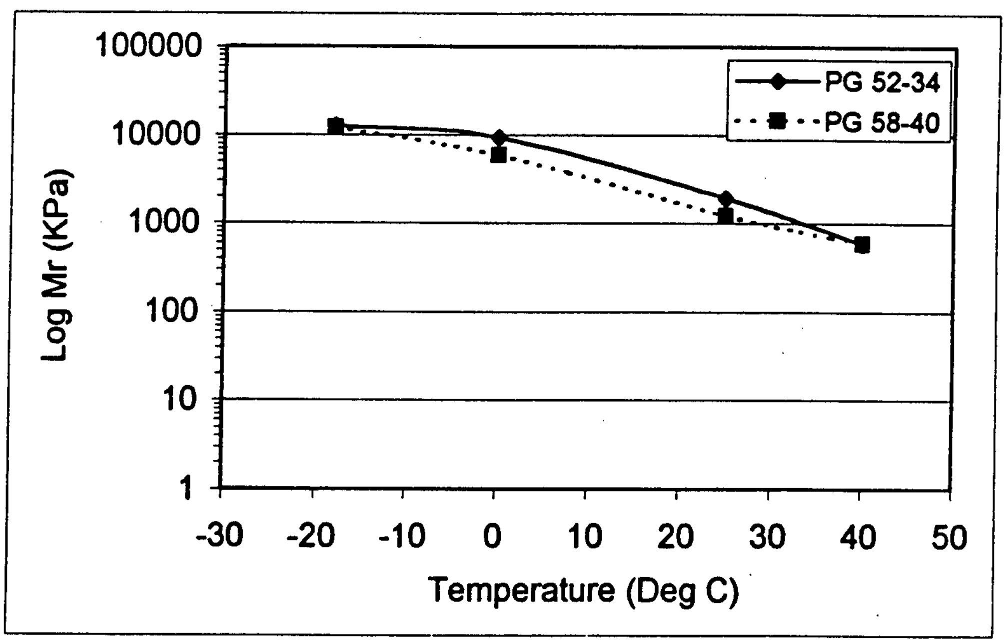


Figure 4.12 Influence of Asphalt Grade on Stiffness

**Moisture Sensitivity**

Table 4.6 provides a summary of the moisture sensitivity results. As expected, the effects of the vacuum saturation and the 24-hour warm water bath caused the samples to swell (increase in volume). Superpave criteria require a minimum tensile strength ratio of 80 percent. The TSRs for the 10 mixtures evaluated were all above 95 percent. Although, still debated, high TSR values such as these may indicate a lower susceptibility to moisture damage. Complete test results are provided in Appendix C.

Table 4.6 Summarized Moisture Sensitivity Results

| Sample ID | Measurement | PG 52-34 Coarse Gradation | | | | PG 52-34 Fine Gradation | | | | PG 58-40 Fine | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GFC | NUC | KLC | CGC | GFF | NUF | KLF | CGF | NUF | KLF |
| Unconditioned Samples | Load (lbf) | 4988.3 | 4970.8 | 4966.2 | 4945.7 | 4958.9 | 4957.0 | 4980.6 | 4962.7 | 4967.3 | 4957.7 |
| | Dry Strength | 25779 | 25705 | 25094 | 25460 | 25082 | 25662 | 25434 | 25616 | 25275 | 24976 |
| Unconditioned Samples | % Air Voids | 6.56 | 6.79 | 6.80 | 7.43 | 6.76 | 6.63 | 6.70 | 7.12 | 6.80 | 7.21 |
| Conditioned Samples | % Air Voids | 6.66 | 7.01 | 6.73 | 7.60 | 6.77 | 6.46 | 6.67 | 7.51 | 6.83 | 7.37 |
| After Vacuum Saturation | % Saturation | 68.37 | 69.30 | 69.39 | 66.74 | 71.53 | 59.22 | 69.87 | 70.23 | 69.24 | 76.58 |
| | % Swell | 3.41 | 4.32 | 3.78 | 3.84 | 3.03 | 3.01 | 3.32 | 4.59 | 3.53 | 3.93 |
| After 140°F 24-hr Water Bath | % Saturation | 86.58 | 104.43 | 79.99 | 82.09 | 99.84 | 79.23 | 86.70 | 82.56 | 89.13 | 108.33 |
| | % Swell | 4.84 | 6.70 | 5.19 | 5.09 | 5.28 | 4.38 | 4.40 | 5.58 | 4.93 | 6.31 |
| | Load (lbf) | 4976.7 | 4981.3 | 4971.2 | 4971.9 | 4957.4 | 4996.2 | 4971.7 | 4973.2 | 4966.9 | 4966.9 |
| | Wet Strength | 24814 | 25096 | 24325 | 25178 | 24338 | 25370 | 24699 | 25170 | 25030 | 24756 |
| Tensile Strength Ratio | TSR | 96.73 | 97.62 | 96.93 | 98.88 | 96.97 | 99.46 | 97.11 | 98.26 | 99.03 | 99.34 |

## DISCUSSION

**Mix Design**

One of the more important mix design issues to discuss is the difficulty in achieving the minimum voids in the mineral aggregate (VMA) criterion. As described in the mix design methodology, eight different gradations were tried in the attempt to meet the 14% Superpave VMA criterion. In fact, this is not an isolated case. If there is a common theme in Superpave experiences, it is a difficulty in achieving the minimum VMA criterion. Kandhal et al. (1998) attribute the problem to the increased compactive effort of the gyratory compactor and the increased use of coarser aggregate mixes.

N.W. McLeod (1956) first presented the concept of volumetric proportioning to the Highway Research Board in 1956. He developed his volumetric criteria based on specimens compacted with a Marshall hammer (75 blows on each side). McLeod concluded that to ensure adequate durability in a mixture compacted to 5 percent air voids, the mixture must contain a minimum VMA of 15 percent and a minimum asphalt content of 4.5 percent. Future work by McLeod (1959) related minimum VMA criteria to nominal maximum particle size of the aggregate. Since VMA is the sum of air voids and voids filled with asphalt, the minimum VMA criteria can be extrapolated to 14 percent for four percent air voids, and 13 percent for three percent air voids. McLeod's original 15% minimum VMA criterion was adopted by the Asphalt Institute in 1964 and revised to include the extrapolated values in 1993 for their Manual Series 2 (MS-2). The revised minimum VMA requirements have also been included in the Superpave mix design. However, the VMA criteria were developed for denser aggregate gradations commonly used in the Marshall mix design. Therefore, it may be questionable to require coarser Superpave mixes to meet the same VMA criteria as denser Marshall mixes.

The rationale behind specifying a minimum VMA percentage is to ensure that the mix contains enough asphalt cement to adequately coat the aggregate particles. This asphalt coating of the aggregate is known as the asphalt film thickness. Adequate film thickness is essential for a long-lasting, durable mix. Kandhal (1998) cites conclusions by Campen et al. (1959) that thicker films produced mixes that were flexible and durable. Thin films produced mixes that were brittle and exhibited excessive cracking, raveling, poor performance, and reduced longevity. Research by Campen et al. (1959) showed an optimum film thickness of 6 to 8 μm. They also found that to achieve the desired 6 to 8 μm thickness the asphalt binder requirement increased as surface areas increased, but at a much lower rate.

Recently, a new approach to ensuring adequate film thickness has surfaced. Rather than use VMA to *indirectly* ensure adequate film thickness, proponents of this new approach suggest estimating the film thickness *directly*. Unfortunately, however, there is an inherent problem in estimating aggregate film thickness—current methods of calculating film thickness assume an average thickness, but not every aggregate particle is going to have the same thickness. Khandal et al. (1998) address this problem by citing work done by Goode and Lufsey (1965) in which the concept of a bitumen index was used to avoid the inference that all particles are coated with the same uniform thickness of asphalt cement. The bitumen index is defined as mass of asphalt cement per area of surface. Goode and Lufsey concluded a minimum bitumen index of 6.0 kg/m$^2$ (0.00123 lb/ft$^2$, which correlates to 6 μm) was sufficient to ensure adequate film thickness.

Kandhal et al. (1998) provide the following equations for the calculation of asphalt film thickness:

$$\text{Volume of Asphalt Binder, } V_b = VMA - V_a \tag{4.1}$$

$$\text{Mass of Asphalt Binder, } W_b = V_b \times \rho_b \times G_b \tag{4.2}$$

$$\text{Mass of Aggregate, } W_{agg} = \frac{W_b}{P_b} \times (100 - P_b) \tag{4.3}$$

Mass of Asphalt per Kg of Aggregate, $W_{b/agg} = \dfrac{W_b}{W_{agg}}$ (4.4)

Asphalt Film Thickness, $AFT = \dfrac{W_{b/agg}}{SA_{agg} \times \rho_w \times G_b}$ (4.5)

Where:

$V_a$ = Air voids
$\rho_w$ = Density of water (1000 kg/m$^3$)
$G_b$ = Specific gravity of the Binder (1.02)
$P_b$ = Asphalt Content
$SA_{agg}$ = Total surface of the aggregate

The total surface area of the aggregate is a function of the gradation. Aggregate surface area was calculated using the procedure outlined in the Asphalt Institute's MS-2 (1993). Results of the aggregate surface area computations are shown in Tables 4.7 and 4.8 for coarse and fine gradations, respectively.

Table 4.7 Total Surface Area Calculation for Coarse Gradation.

| Sieve Size | Percent Passing | Surface Area Factor | Surface Area |
|---|---|---|---|
| 19 | 100.0 | 0.41 | 0.41 |
| 12.5 | 93.2 | | |
| 9.5 | 66.2 | | |
| 4.75 | 47.3 | 0.41 | 0.19393 |
| 2.36 | 33.8 | 0.82 | 0.27716 |
| 1.18 | 23.0 | 1.64 | 0.3772 |
| 0.600 | 16.2 | 2.87 | 0.46494 |
| 0.300 | 12.2 | 6.14 | 0.74908 |
| 0.150 | 8.1 | 12.29 | 0.99549 |
| 0.075 | 4.1 | 32.77 | 1.34357 |
| | | Total: | 4.81137 |

Table 4.8 Total Surface Area Calculation for Fine Gradation.

| Sieve Size | Percent Passing | Surface Area Factor | Surface Area |
|---|---|---|---|
| 19 | 100.0 | 0.41 | 0.41 |
| 12.5 | 96.1 | | |
| 9.5 | 83.1 | | |
| 4.75 | 70.1 | 0.41 | 0.28741 |
| 2.36 | 57.1 | 0.82 | 0.46822 |
| 1.18 | 44.2 | 1.64 | 0.72488 |
| 0.600 | 31.2 | 2.87 | 0.89544 |
| 0.300 | 18.2 | 6.14 | 1.11748 |
| 0.150 | 7.8 | 12.29 | 0.95862 |
| 0.075 | 3.9 | 32.77 | 1.27803 |
| | | **Total:** | **6.14008** |

Equations 4.1 through 4.5 were used to calculate the asphalt film thicknesses for the mixtures in this project. The results are shown below in Table 4.9. It should be noted that all of the asphalt film thickness values exceed the minimum of 6 μm recommended by Campen et al (1959). In fact, most fell within the optimum range of 8-10 μm recommended by Kandhal et al.(1998) and by Kandhal and Chakraborty (1996). As expected, the coarse mixes have a higher AFT than the fines since they have fewer total voids and less surface area.

Table 4.9 Asphalt Film Thickness Calculations

| Aggregate | $P_b$ (%) | $V_a$ (%) | VMA (%) | $SA_{agg}$ ($m^2$/kg) | $V_b$ (%) | $W_b$ (kg) | $W_{agg}$ (kg) | $W_{b/agg}$ (kg) | AFT (μm) |
|---|---|---|---|---|---|---|---|---|---|
| GFC | 4.30 | 3.00 | 11.50 | 4.811 | 8.50 | 86.7 | 1929.6 | 0.0449 | 9.156 |
| GFF | 4.80 | 3.00 | 12.40 | 6.140 | 9.40 | 95.88 | 1901.6 | 0.0504 | 8.051 |
| NUC | 4.95 | 3.00 | 11.25 | 4.811 | 8.25 | 84.15 | 1615.9 | 0.0521 | 10.612 |
| NUF | 5.00 | 3.00 | 10.50 | 6.140 | 7.50 | 76.5 | 1453.5 | 0.0526 | 8.404 |
| KLC | 4.20 | 3.00 | 9.00 | 4.811 | 6.00 | 61.2 | 1395.9 | 0.0438 | 8.933 |
| KLF | 5.20 | 3.00 | 10.80 | 6.140 | 7.80 | 79.56 | 1450.4 | 0.0549 | 8.758 |
| CGC | 4.70 | 3.00 | 10.50 | 4.811 | 7.50 | 76.5 | 1551.2 | 0.0493 | 10.049 |
| CGF | 5.00 | 3.00 | 11.50 | 6.140 | 8.50 | 86.7 | 1647.3 | 0.0526 | 8.404 |
| NUF (58-40) | 4.90 | 3.00 | 11.40 | 6.140 | 8.40 | 85.68 | 1662.9 | 0.0515 | 8.227 |
| KLF (58-40) | 4.90 | 3.00 | 11.30 | 6.140 | 8.30 | 84.66 | 1643.1 | 0.0515 | 8.227 |

Kandhal et al. (1998) recommended lowering the Superpave minimum VMA criterion by 1.2 to 1.5 percent based on the results of their research, and specifying an 8 μm minimum AFT. Unfortunately, while all the mixes in the Superpave project exceed the recommended 8 μm minimum AFT, even lowering the VMA criteria by 1.5 percent would only allow the Granite Falls Coarse mixture to meet the 13% minimum.

Another interesting issue is the apparent susceptibility of the coarse gradations to rutting according to the compaction data. Research has shown mixtures exceeding 98% of maximum density at $N_{max}$ may be more susceptible to rutting than those that remain below 98% of maximum density (Brown et al., 1996). Additionally, since three of the four coarse aggregates exceeded the 98% maximum density criterion, the problem is probably systemic to the gradation rather than any one specific aggregate. Five of the six fine gradations have densities greater than 89% at $N_{ini}$. Therefore, it is suspected the fine gradation might exhibit compactibility problems such as tenderness during construction and instability when subjected to traffic (Brown et al. 1996).

The concern over failing the $N_{ini}$ and $N_{max}$ criteria is debated. To date, there is no irrefutable research correlating the failure of the $N_{ini}$ criterion with susceptibility to tenderness nor the failure of the $N_{max}$ criterion with increased rutting potential. In fact, mounting research (Brown, 1996 & 1998; Habib, 1998; Huber, 1996) is supporting the belief that all three Superpave gyration criteria ($N_{ini}$, $N_{des}$, $N_{max}$) should be lowered (especially with low-volume designs). Superpave Team Leader, Paul Mack (1998), addressed this concern by stating the problem is currently being evaluated in preparation of a possible revision to the Superpave N-design table. Mack (1998) specifically addresses the failure of the $N_{ini}$ criterion by fine graded mixes stating such failure is common and should not eliminate their use, particularly on low-volume pavements. More concern over the validity of the density criteria arose when an evaluation of four different Superpave gyratory compactors (Texas, Pine, Troxler, and Rainhart) by McGennis et al. (1996) showed a high degree of variability in $N_{ini}$ results.

**Resilient Modulus**

Although the results of the resilient modulus testing were variable, some general conclusions can still be made. As expected, the resilient modulus values decrease considerably as temperature increases. The decreasing values are the result of the softening of the asphalt binder as temperatures increase. Except for the 0°C temperature, the coefficient of variation values fell well below the 10-20 percent range recommended by Al-Sugair and Almudaiheem (1992). Additionally, the COV values follow the expected trend of increasing at the extreme temperatures. Stroup-Gardiner and Newcomb (1994) attributed the increase in variability at the coldest and warmest temperatures as a function of sensor noise and the low stiffness of the binder, respectively (Timm, 1997).

The lack of a significant difference in the resilient modulus values between the coarse and fine gradations is surprising. It was expected the increased amount of crushed aggregate found in the coarse mixes (except for the Cedar Grove gravel) would have resulted in a stiffer mix. As stated earlier, the mix containing the Kasota limestone aggregate behaved differently than those made with other aggregates.

In Figure 4.12, the PG 58-40 grade asphalt has a slightly lesser slope of temperature susceptibility than the PG 52-34 asphalt. However, at the highest and lowest test temperatures the values were nearly identical. The effect of different asphalt grades on coarse gradations should be investigated.

## Moisture Sensitivity

The range of the tensile strength ratio results was somewhat greater and less variable than expected. The TSR values shown in Table 4.6 would seem to indicate the differences in gradation, aggregate and asphalt grade had no significant effect on the moisture sensitivity of the mixtures. Such high TSR results may be explained by work done by McGennis et al. (1996) who concluded specimens compacted with a Superpave gyratory compactor resulted in significantly higher TSR values. Additionally, Brown et al., (1996) noted the low reliability and lack of a satisfactory relationship between laboratory and field conditions as a chronic problem with moisture sensitivity tests.

## CHAPTER FIVE

## CONCLUSIONS AND RECOMMENDATIONS

### CONCLUSIONS

1. Locally available Minnesota aggregates such as Lakeland sand, Granite Falls granite, New Ulm quartzite, Kasota limestone, and Cedar Grove gravel do meet Superpave aggregate consensus property criteria for low-volume roads.
2. Meeting Superpave's minimum VMA and VFA criteria was very difficult possibly due to the low angularity of the Lakeland aggregate. Recall that the addition of fine-graded Dresser traprock allowed for an increase in VMA. Lowering the target air void content to 3% resulted in compliant VFA, but did not affect the VMA results. Use of a more angular fine aggregate would help increase the VMA.
3. All six fine-graded mixtures did not meet the $N_{ini}$ criterion indicating fine-graded mixtures produced with the Lakeland sand may be susceptible to tenderness problems. There appeared to be no significant difference in tenderness susceptibility between the different aggregates evaluated.
4. All four coarse-graded mixtures did not meet the $N_{max}$ criterion indicating coarse-graded mixtures produced with the Lakeland sand may experience premature permanent deformation. There appeared to be no significant difference in susceptibility to permanent deformation between the four coarse aggregates evaluated. Permanent Deformation of coarse-graded mixes was also experienced at WestTrack, the Federal Highway Administration's asphalt test track. Researchers at WesTrack concluded that even at higher asphalt contents the aggregate particles in

the coarse-graded mixes did not interlock to form a stronger stone skeleton as was the case with the fine-graded mixes.

5. There was no significant difference in indications of susceptibility to either tenderness or permanent deformation between the two asphalt grades evaluated.
6. The results of the resilient modulus tests were highly variable. Although high variability is not uncommon to resilient modulus testing, the 1 to 23 percent average coefficients of variance range from this study was greater than the typical 6 to 20 percent range presented by Timm (1997).
7. Except for the Kasota limestone which produced slightly greater resilient modulus values, the different aggregates evaluated in this study had no significant effect on resilient modulus. To date, however, no direct correlation has been made between resilient modulus values and long-term susceptibility to permanent deformation.
8. There was no significant difference in resilient modulus values between the coarse and fine gradations evaluated in this study. Therefore, no difference in susceptibility to temperature variation is expected between the two gradations.
9. Mixes produced with the PG 52-34 asphalt binder had higher resilient modulus results at intermediate temperatures than those produced with the PG 58-40 binder. There was no significant difference in resilient modulus values between the two binders at the highest and lowest temperatures tested. Therefore, no significant difference in susceptibility to temperature variation (at the temperature range evaluated) is expected between the two asphalt binder grades.
10. All mixes evaluated met the Superpave moisture sensitivity criterion. The higher asphalt contents associated with the relatively low 3% design air void content was

the probable cause for the high TSR values. High TSR values indicate the higher asphalt content associated with the lower target air void content may improve the durability of low-volume road mixtures.

11. There was no significant difference in moisture sensitivity results between the coarse and fine gradations; granite, quartzite, limestone, and gravel coarse aggregates; or PG 52-34 and PG 58-40 asphalt grades evaluated in this study. As concluded by Stroup-Gardiner and Newcomb (1994), lack of a significant difference between material types indicates moisture sensitivity may be more dependent on volumetric parameters than on types of material.
12. Adequate mixture designs can be produced using locally available MN aggregate allowing effective use of the Superpave mix design system at the local government level. Huber (1996) also determined Superpave could be effectively used at the local government level after evaluating the performance of standard, commercially available Indiana aggregates used in low-volume Superpave mix designs.

## RECOMMENDATIONS

1. Recommend using a target air void content of three percent. The higher asphalt content associated with a lower air void target would increase the long-term durability of the pavement. The decrease in stability associated with pavements constructed with higher asphalt contents is offset by the lower volume of heavy-truck traffic experienced on low-volume roads.
2. The low angularity of the Lakeland sand resulted in difficulties meeting Superpave volumetric criteria. A more angular, locally available aggregate is necessary to produce

mixtures that can meet the volumetric criteria. A study should be conducted to investigate the benefit of using a more angular fine aggregate. This study should include an economic evaluation.

3. If volumetric criteria cannot be met, a possible solution would be to lower the target air void content and take the necessary precautions to overcome any tenderness problems that may result. Wolters (1998) recommends the following construction techniques to overcome tenderness problems: Use two vibratory, double-drum, steel-wheeled rollers operating in tandem immediately following the paver for breakdown rolling. Once the mix cools into the tenderness zone (121°C to 77°C (250°F to 170°F)) use pneumatic rollers to continue compaction without pavement damage. When the mix has cooled enough to allow sufficient stability, use a steel-wheeled roller to roll out any pneumatic-tire marks.
4. Recommend use of finer gradations. They are more economical, and results show more stable at $N_{max}$. Potential for rutting is a more severe problem than tenderness since tenderness can be overcome during construction, but permanent deformation requires costly repairs.
5. The effects of different asphalt binder grades on coarse graded mixes should be evaluated.
6. Performance testing on mixtures produced with the locally available MN aggregate was not completed. Sole Reliance on the $N_{ini}$ and $N_{max}$ results to predict tenderness and rutting susceptibility is cautioned as these measurements are merely initial indications of potential performance problems. Although performance prediction tests are not required in Superpave's Level I mix design, the completion of prediction tests for permanent

deformation, fatigue cracking or low temperature cracking is highly recommended for any mix design intended to become a standard government design.

7. If performance testing shows the higher grade asphalt binder produces better results, an economic analysis should be completed to determine whether the improvements in predicted long-term pavement performance justify the increased cost of the binder.

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# APPENDIX A
## Initial Asphalt Binder Content Calculation Example

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Project: SUPERPAVE | Technician: | | | | Date: | | |
| Gradation: | [ ] Above (fine)<br>[X] Below | the Restricted Zone | Nom. Max. Size (mm): | 12.5 | Batch Weight $W_s$, (g) | 12,000 | |
| Asphalt Sourse: KOCH | Grade: | | | | Polymer: | | |
| $T_{mix}$: 138 °C | $T_{comp}$: 128 ° | Compactor: Brovold | | Nini 7 | Ndes 76 | Nmax 117 | |

### Part I: Calculate Combined Aggregate Properties

| Aggregate Fraction | Fine (<9.5mm) | Coarse (>9.5mm) | Combined |
|---|---|---|---|
| Aggregate Source | Lakeland | Granite Falls | $G_{combined} = \dfrac{1}{\left(\dfrac{P_{fine}}{G_{fine}} + \dfrac{P_{coarse}}{G_{coarse}}\right)}$ |
| Batch Weight (W) | 7,664 | 4,336 | |
| Proportion $P=W/W_s$ | 0.639 | 0.361 | |
| Bulk Specific Gravity ($G_{sb}$) | 2.602 | 2.757 | 2.6560 |
| Apparent Specific Gravity ($G_{sa}$) | 2.77 | 2.797 | 2.7797 |
| Effective Specific Gravity: $G_{se} = G_{sb} + 0.6(G_{sa} - G_{sb})$ | | | 2.7302 |

### Part II: Calculate Trial Asphalt Binder Content (Assume $G_b = 1.02$)

| Aggregate Factor ($F_s$) | | Vol. of Absorbed Binder ($V_{ba}$) | | Vol. of Effective Binder ($B_{be}$) | | Trial Binder Content ($P_{bi}$) | |
|---|---|---|---|---|---|---|---|
| $F_s = \dfrac{0.95 \times (1-0.04)}{\left(\dfrac{0.05}{G_b} + \dfrac{0.95}{G_{se}}\right)}$ | | $V_{ba} = F_s \times \left(\dfrac{1}{G_{sb}} - \dfrac{1}{G_{se}}\right)$ | | $V_{be} = 0.176 - 0.0675 \log(S_n)$ ($S_n$ = nom. Max. size, mm) | | $P_{bi} = \dfrac{G_b \times (V_{be} + V_{ba})}{(G_b \times (V_{be} + V_{ba})) + F_s}$ | |
| $F_s =$ | 2.29735 | $V_{ba} =$ | 0.02352 | $V_{be} =$ | 0.10196 | $P_{bi} =$ | 5.277 |

### Part III: Mix & Compact (2 Compacted Specimens, 1 $G_{mm}$)

| Mix Data | | Spec. Ht (mm) | 1 | 2 | $G_{mb}$ | 1 | 2 |
|---|---|---|---|---|---|---|---|
| Target $P_b$ (%) | 5.28 | Sample 1 | 110.35 | 110.74 | $W_{dry}$ (g) A | 4775.9 | 4776.8 |
| Target $W_b$ (g) | 668.55 | Sample 2 | 110.4 | 110.71 | $W_{inwater}$ (g) C | 2822.6 | 2824.2 |
| Actual $W_b$ (g) | | Sample 3 | 110.36 | 110.66 | $W_{ssd}$ (g) B | 4780.4 | 4781.3 |
| Actual $P_b$ (%) | 5.1 | Sample 4 | 110.36 | 110.75 | $G_{mb}$=A/(B-C) | 2.4394 | 2.4408 |
| $G_{mm}$ | 2.509 | Average | 110.37 | 110.72 | Corrected $G_{mb}$ @ $N_{des}$ | 2.413 | 2.415 |
| | | | | | $V_a$ @ $N_{des}$ | 3.826 | 3.747 |
| | | | | | $V_a$ Average | 3.786 | |
| | | | | | $V_a$ Actual | 3.79 | |

$$\text{Target } W_b = W_s\left(\frac{\text{Target } P_b}{1 - \text{Target } P_b}\right) \qquad V_a = \left(\frac{G_{mm} - G_{mb}}{G_{mm}}\right)$$

### Part IV: Calculate New Target Binder Content ($P_{b,est.}$)

| Pb,est. = Pb,old - (0.4 x (4 - Va)) Note: Pb,old = Actual Pb from Part III and Va = Va @ Ndes | | | | | | | |
|---|---|---|---|---|---|---|---|
| $P_{b,est}$ - 0.5 = | 4.51 | $P_{b,est}$ = | 5.01 | $P_{b,est}$ + 0.5 = | 5.51 | $P_{b,est}$ + 1.0 = | 6.01 |
| $W_b$ (g) = | 567.36 | $W_b$ (g) = | 633.51 | $W_b$ (g) = | 700.37 | $W_b$ (g) = | 767.93 |

*Except for header section, shading denotes input cell.

# APPENDIX B

## Resilient Modulus Test Results (-18°C)

| Temp = 0F | | Res. Mod | | | Std. Dev. | | | Coeficient of Variance (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Freqency | ID (deg) | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 |
| GFC (4.5%) | 1 (0) | 2172.63 | 2283.94 | 2190.33 | 279.04 | 349.10 | 146.02 | 12.84 | 15.28 | 6.67 |
| | 1 (90) | 1391.62 | 1583.59 | 1618.22 | 127.71 | 246.06 | 224.29 | 9.18 | 15.54 | 13.86 |
| | 2 (0) | 1214.23 | 1565.29 | 1577.36 | 265.28 | 456.89 | 515.05 | 21.85 | 29.19 | 32.65 |
| | 2 (90) | 1492.35 | 1187.01 | 1412.87 | 55.65 | 209.98 | 262.60 | 3.73 | 17.69 | 18.59 |
| | 3 (0) | 2095.81 | 1936.28 | 2218.58 | 346.64 | 434.46 | 238.61 | 16.54 | 22.44 | 10.75 |
| | 3 (90) | 1393.97 | 1584.06 | 1602.93 | 251.37 | 222.49 | 380.62 | 18.03 | 14.05 | 23.74 |
| GFF (5.1%) | 1 (0) | 1993.84 | 2309.81 | 2302.62 | 227.40 | 165.50 | 116.69 | 11.40 | 7.17 | 5.07 |
| | 1 (90) | 1368.26 | 1284.13 | 1191.02 | 166.10 | 128.12 | 49.01 | 12.14 | 9.98 | 4.11 |
| | 2 (0) | 1473.61 | 1904.68 | 1459.01 | 326.77 | 419.95 | 374.44 | 22.17 | 22.05 | 25.66 |
| | 2 (90) | 1361.09 | 1667.67 | 1742.96 | 165.13 | 325.95 | 280.07 | 12.13 | 19.55 | 16.07 |
| | 3 (0) | 2119.95 | 1775.52 | 2123.50 | 529.17 | 332.36 | 1269.45 | 24.96 | 18.72 | 59.78 |
| | 3 (90) | 1661.60 | 1764.19 | 1907.43 | 234.31 | 214.35 | 192.63 | 14.10 | 12.15 | 10.10 |
| NUC (4.7%) | 1 (0) | 1608.95 | 1563.11 | 1456.97 | 449.82 | 477.04 | 644.16 | 27.96 | 30.52 | 44.21 |
| | 1 (90) | 2106.77 | 2747.99 | 2456.10 | 105.65 | 246.34 | 335.72 | 5.01 | 8.96 | 13.67 |
| | 2 (0) | 2116.92 | 2063.80 | 2099.05 | 431.04 | 374.70 | 193.24 | 20.36 | 18.16 | 9.21 |
| | 2 (90) | 1643.43 | 1518.49 | 1518.89 | 303.73 | 283.12 | 245.65 | 18.48 | 18.64 | 16.17 |
| | 3 (0) | 1541.95 | 2173.93 | 2711.84 | 142.61 | 276.18 | 351.04 | 9.25 | 12.70 | 12.94 |
| | 3 (90) | 1850.71 | 2141.86 | 2151.38 | 220.13 | 245.63 | 130.79 | 11.89 | 11.47 | 6.08 |
| NUF (5.1%) | 1 (0) | 1985.00 | 2068.07 | 1996.98 | 259.03 | 271.19 | 139.74 | 13.05 | 13.11 | 7.00 |
| | 1 (90) | 1714.72 | 1761.84 | 1969.99 | 287.21 | 308.75 | 593.95 | 16.75 | 17.52 | 30.15 |
| | 2 (0) | 1374.27 | 1473.09 | 1563.87 | 223.00 | 68.85 | 80.99 | 16.23 | 4.67 | 5.18 |
| | 2 (90) | 1663.11 | 1689.10 | 1683.02 | 314.84 | 231.39 | 204.83 | 18.93 | 13.70 | 12.17 |
| | 3 (0) | 1709.02 | 2115.77 | 1843.76 | 223.76 | 185.10 | 299.73 | 13.09 | 8.75 | 16.26 |
| | 3 (90) | 1893.65 | 1862.69 | 2355.57 | 402.18 | 234.12 | 435.04 | 21.24 | 12.57 | 18.47 |
| KLC (4.4%) | 1 (0) | 1402.17 | 1403.41 | 1387.74 | 164.14 | 70.54 | 115.45 | 11.71 | 5.03 | 8.32 |
| | 1 (90) | 1686.70 | 1625.26 | 1867.27 | 171.31 | 168.12 | 185.71 | 10.16 | 10.34 | 9.95 |
| | 2 (0) | 1370.36 | 1602.38 | 1504.30 | 288.72 | 341.35 | 360.36 | 21.07 | 21.30 | 23.96 |
| | 2 (90) | 1414.69 | 1592.67 | 1684.07 | 237.50 | 231.46 | 274.47 | 16.79 | 14.53 | 16.30 |
| | 3 (0) | 1905.47 | 1951.13 | 1932.02 | 422.76 | 464.76 | 490.34 | 22.19 | 23.82 | 25.38 |
| | 3 (90) | 1648.07 | 1595.88 | 1684.02 | 289.64 | 372.33 | 412.53 | 17.57 | 23.33 | 24.50 |
| KLF (5.1%) | 1 (0) | 1866.45 | 1986.83 | 1784.56 | 202.28 | 289.10 | 172.60 | 10.84 | 14.55 | 9.67 |
| | 1 (90) | 1499.52 | 1389.03 | 1465.26 | 186.05 | 134.70 | 100.87 | 12.41 | 9.70 | 6.88 |
| | 2 (0) | 2207.94 | 1774.98 | 1809.16 | 1099.44 | 173.92 | 297.18 | 49.79 | 9.80 | 16.43 |
| | 2 (90) | 2249.48 | 2229.46 | 2323.93 | 139.10 | 459.21 | 140.06 | 6.18 | 20.60 | 6.03 |
| | 3 (0) | 1764.55 | 2050.67 | 1923.62 | 564.42 | 393.72 | 424.68 | 31.99 | 19.20 | 22.08 |
| | 3 (90) | 1825.91 | 1879.79 | 1478.32 | 156.18 | 245.23 | 108.58 | 8.55 | 13.05 | 7.35 |
| CGC (4.6%) | 1 (0) | 1299.18 | 1511.62 | 1539.62 | 483.44 | 359.96 | 350.13 | 37.21 | 23.81 | 22.74 |
| | 1 (90) | 2111.77 | 3613.15 | 2303.79 | 426.76 | 625.29 | 586.81 | 20.21 | 17.31 | 25.47 |
| | 2 (0) | 1299.69 | 2308.48 | 2627.92 | 201.73 | 245.90 | 399.42 | 15.52 | 10.65 | 15.20 |
| | 2 (90) | 1524.06 | 1693.85 | 1814.87 | 278.77 | 266.90 | 423.50 | 18.29 | 15.76 | 23.33 |
| | 3 (0) | 1318.51 | 1269.66 | 1543.28 | 170.94 | 307.04 | 168.84 | 12.96 | 24.18 | 10.94 |
| | 3 (90) | 2441.10 | 2232.04 | 2552.04 | 327.86 | 622.82 | 1078.33 | 13.43 | 27.90 | 42.25 |
| CGF (5.0%) | 1 (0) | 1645.13 | 1634.44 | 1943.62 | 130.20 | 137.77 | 304.36 | 7.91 | 8.43 | 15.66 |
| | 1 (90) | 1633.10 | 1177.91 | 1413.31 | 234.75 | 207.59 | 338.02 | 14.37 | 17.62 | 23.92 |
| | 2 (0) | 1569.45 | 1670.77 | 1670.86 | 170.42 | 204.32 | 257.28 | 10.86 | 12.23 | 15.40 |
| | 2 (90) | 1506.24 | 2188.26 | 2463.16 | 178.43 | 207.99 | 248.63 | 11.85 | 9.50 | 10.09 |
| | 3 (0) | 1488.94 | 1370.55 | 1494.91 | 249.85 | 22.30 | 233.93 | 16.78 | 1.63 | 15.65 |
| | 3 (90) | 1437.06 | 1115.99 | 1318.76 | 262.98 | 147.68 | 234.53 | 18.30 | 13.23 | 17.78 |
| NUF (58-40) (4.9%) | 1 (0) | 1859.03 | 1680.71 | 1923.09 | 696.01 | 228.76 | 200.71 | 37.44 | 13.61 | 10.44 |
| | 1 (90) | 1723.73 | 1561.61 | 1221.76 | 351.40 | 521.99 | 116.91 | 20.39 | 33.43 | 9.57 |
| | 2 (0) | 1308.80 | 1177.77 | 1412.09 | 104.70 | 128.39 | 153.85 | 8.00 | 10.90 | 10.89 |
| | 2 (90) | 1577.23 | 1553.64 | 1669.22 | 97.46 | 150.10 | 186.69 | 6.18 | 9.66 | 11.18 |
| | 3 (0) | 2100.99 | 2167.08 | 2196.59 | 252.89 | 97.41 | 282.55 | 12.04 | 4.49 | 12.86 |
| | 3 (90) | 1800.88 | 1792.76 | 1842.92 | 218.50 | 161.63 | 148.51 | 12.13 | 9.02 | 8.06 |
| KLF (58-40) (4.9%) | 1 (0) | 1846.81 | 1836.68 | 1926.72 | 180.38 | 159.19 | 229.46 | 9.77 | 8.67 | 11.91 |
| | 1 (90) | 1864.91 | 2114.13 | 2103.62 | 103.07 | 140.20 | 86.16 | 5.53 | 6.63 | 4.10 |
| | 2 (0) | 1830.09 | 1699.25 | 1864.09 | 254.89 | 177.33 | 221.06 | 13.93 | 10.44 | 11.86 |
| | 2 (90) | 1941.27 | 1895.34 | 1820.74 | 251.63 | 176.33 | 64.18 | 12.96 | 9.30 | 3.52 |
| | 3 (0) | 1427.18 | 1116.37 | 1173.38 | 358.89 | 235.26 | 257.48 | 25.15 | 21.07 | 21.94 |
| | 3 (90) | 1697.17 | 2005.81 | 1895.63 | 247.75 | 770.66 | 224.73 | 14.60 | 38.42 | 11.86 |

# APPENDIX B

## Resilient Modulus Test Results (0°C)

| Temp = 34F | | Res. Mod | | | Std. Dev. | | | Coeficient of Variance (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Freqency | ID (deg) | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 |
| | 1 (0) | 1231.73 | 1261.85 | 1243.96 | 143.05 | 45.76 | 47.32 | 11.61 | 3.63 | 3.80 |
| | 1 (90) | 1189.42 | 1316.83 | 1308.97 | 116.78 | 91.91 | 30.40 | 9.82 | 6.98 | 2.32 |
| GFC | 2 (0) | 1141.11 | 979.11 | 1182.30 | 154.92 | 64.99 | 26.54 | 13.58 | 6.64 | 2.25 |
| (4.5%) | 2 (90) | 1484.32 | 1480.81 | 1558.65 | 120.14 | 123.41 | 64.09 | 8.09 | 8.33 | 4.11 |
| | 3 (0) | 1222.55 | 1078.15 | 1117.57 | 77.68 | 94.31 | 32.81 | 6.35 | 8.75 | 2.94 |
| | 3 (90) | 1701.06 | 1600.36 | 1658.16 | 215.56 | 87.50 | 48.82 | 12.67 | 5.47 | 2.94 |
| | 1 (0) | 1303.46 | 1290.13 | 1313.70 | 196.80 | 95.45 | 79.21 | 15.10 | 7.40 | 6.03 |
| | 1 (90) | 1273.38 | 1279.33 | 1356.05 | 109.36 | 46.21 | 77.45 | 8.59 | 3.61 | 5.71 |
| GFF | 2 (0) | 1342.22 | 1324.13 | 1289.75 | 107.01 | 76.76 | 19.37 | 7.97 | 5.80 | 1.50 |
| ( 5.1%) | 2 (90) | 1449.08 | 1522.79 | 1441.38 | 51.49 | 74.49 | 28.50 | 3.55 | 4.89 | 1.98 |
| | 3 (0) | 1570.86 | 1441.20 | 1460.77 | 321.31 | 100.96 | 49.34 | 20.45 | 7.01 | 3.38 |
| | 3 (90) | 1288.46 | 1268.12 | 1358.32 | 104.87 | 34.84 | 40.80 | 8.14 | 2.75 | 3.00 |
| | 1 (0) | 1048.69 | 1083.96 | 1095.61 | 50.65 | 46.79 | 22.89 | 4.83 | 4.32 | 2.09 |
| | 1 (90) | 1179.38 | 1151.28 | 1211.22 | 100.84 | 54.62 | 37.74 | 8.55 | 4.74 | 3.12 |
| NUC | 2 (0) | 1183.74 | 1111.77 | 1135.64 | 76.33 | 44.88 | 25.40 | 6.45 | 4.04 | 2.24 |
| (4.7%) | 2 (90) | 1333.05 | 1425.85 | 1329.57 | 204.10 | 117.76 | 154.90 | 15.31 | 8.26 | 11.65 |
| | 3 (0) | 1193.35 | 1217.75 | 1208.64 | 87.71 | 55.12 | 53.88 | 7.35 | 4.53 | 4.46 |
| | 3 (90) | 1195.34 | 1119.76 | 1120.18 | 95.10 | 68.53 | 82.08 | 7.96 | 6.12 | 7.33 |
| | 1 (0) | 1286.75 | 1305.75 | 1290.82 | 91.41 | 152.07 | 93.28 | 7.10 | 11.65 | 7.23 |
| | 1 (90) | 1232.36 | 1297.36 | 1325.87 | 119.49 | 116.24 | 85.61 | 9.70 | 8.96 | 6.46 |
| NUF | 2 (0) | 1306.14 | 1343.82 | 1348.11 | 103.55 | 58.77 | 38.56 | 7.93 | 4.37 | 2.86 |
| ( 5.1%) | 2 (90) | 1480.50 | 1435.83 | 1496.42 | 92.86 | 104.15 | 50.91 | 6.27 | 7.25 | 3.40 |
| | 3 (0) | 1419.75 | 1350.29 | 1386.60 | 196.15 | 85.71 | 63.88 | 13.82 | 6.35 | 4.61 |
| | 3 (90) | 1413.14 | 1348.87 | 1357.96 | 97.46 | 128.01 | 46.35 | 6.90 | 9.49 | 3.41 |
| | 1 (0) | 1407.99 | 1311.37 | 1377.39 | 101.90 | 138.25 | 43.88 | 7.24 | 10.54 | 3.19 |
| | 1 (90) | 1496.87 | 1528.41 | 1580.33 | 283.65 | 97.81 | 87.86 | 18.95 | 6.40 | 5.56 |
| KLC | 2 (0) | 1223.46 | 1290.74 | 1254.71 | 100.64 | 68.53 | 43.97 | 8.23 | 5.31 | 3.50 |
| ( 4.4%) | 2 (90) | 1374.99 | 1297.12 | 1386.99 | 98.95 | 72.15 | 67.60 | 7.20 | 5.56 | 4.87 |
| | 3 (0) | 1324.96 | 1321.98 | 1393.36 | 110.24 | 121.39 | 22.23 | 8.32 | 9.18 | 1.60 |
| | 3 (90) | 1420.88 | 1437.80 | 1343.29 | 99.49 | 100.97 | 48.59 | 7.00 | 7.02 | 3.62 |
| | 1 (0) | 1414.75 | 1474.61 | 1516.36 | 95.84 | 56.80 | 50.17 | 6.77 | 3.85 | 3.31 |
| | 1 (90) | 1235.29 | 1304.08 | 1360.78 | 61.52 | 67.11 | 54.98 | 4.98 | 5.15 | 4.04 |
| KLF | 2 (0) | 1333.81 | 1326.25 | 1446.78 | 77.87 | 75.28 | 80.78 | 5.84 | 5.68 | 5.58 |
| (5.1%) | 2 (90) | 1160.16 | 1208.38 | 1173.19 | 80.64 | 134.93 | 39.03 | 6.95 | 11.17 | 3.33 |
| | 3 (0) | 1368.82 | 1383.66 | 1423.98 | 77.12 | 72.23 | 81.37 | 5.63 | 5.22 | 5.71 |
| | 3 (90) | 1229.29 | 1227.13 | 1220.99 | 94.21 | 71.68 | 64.08 | 7.66 | 5.84 | 5.25 |
| | 1 (0) | 1322.69 | 1358.04 | 1385.72 | 133.60 | 37.05 | 28.06 | 10.10 | 2.73 | 2.03 |
| | 1 (90) | 1353.11 | 1370.87 | 1402.66 | 79.33 | 76.52 | 45.46 | 5.86 | 5.58 | 3.24 |
| CGC | 2 (0) | 1383.31 | 1357.07 | 1378.15 | 122.36 | 43.72 | 36.77 | 8.85 | 3.22 | 2.67 |
| (4.6%) | 2 (90) | 1190.26 | 1198.69 | 1230.81 | 109.52 | 97.29 | 79.14 | 9.20 | 8.12 | 6.43 |
| | 3 (0) | 1257.28 | 1222.3[illegible] | 1270.63 | 82.05 | 58.97 | 47.62 | 6.53 | 4.82 | 3.75 |
| | 3 (90) | 1252.99 | 1284.41 | 1319.83 | 104.77 | 94.35 | 73.25 | 8.36 | 7.35 | 5.55 |
| | 1 (0) | 1268.80 | 1239.35 | 1245.56 | 190.05 | 82.21 | 62.77 | 14.98 | 6.63 | 5.04 |
| | 1 (90) | 1273.26 | 1175.71 | 1377.03 | 118.27 | 66.29 | 59.38 | 9.29 | 5.64 | 4.31 |
| CGF | 2 (0) | 1457.37 | 1439.52 | 1445.20 | 95.42 | 90.11 | 87.12 | 6.55 | 6.26 | 6.03 |
| (5.0%) | 2 (90) | 1272.35 | 1269.28 | 1259.43 | 38.81 | 81.64 | 79.15 | 3.05 | 6.43 | 6.28 |
| | 3 (0) | 1260.31 | 1284.51 | 1356.33 | 26.27 | 88.78 | 34.98 | 2.08 | 6.91 | 2.58 |
| | 3 (90) | 1379.65 | 1402.81 | 1431.20 | 23.24 | 37.80 | 49.28 | 1.68 | 2.69 | 3.44 |
| | 1 (0) | 791.27 | 824.33 | 856.41 | 54.52 | 47.47 | 40.21 | 6.89 | 5.76 | 4.70 |
| | 1 (90) | 849.43 | 813.27 | 807.09 | 73.31 | 48.14 | 17.29 | 8.63 | 5.92 | 2.14 |
| NUF | 2 (0) | 921.29 | 947.65 | 969.95 | 48.13 | 28.26 | 38.74 | 5.22 | 2.98 | 3.99 |
| (58-40) | 2 (90) | 768.31 | 786.17 | 780.62 | 46.44 | 76.95 | 23.11 | 6.04 | 9.79 | 2.96 |
| (4.9%) | 3 (0) | 894.92 | 920.48 | 966.41 | 25.84 | 39.96 | 22.47 | 2.89 | 4.34 | 2.33 |
| | 3 (90) | 829.44 | 824.79 | 797.74 | 32.90 | 40.17 | 4.47 | 3.97 | 4.87 | 0.56 |
| | 1 (0) | 832.51 | 838.55 | 828.51 | 26.36 | 33.46 | 31.44 | 3.17 | 3.99 | 3.80 |
| | 1 (90) | 829.29 | 852.16 | 842.86 | 36.36 | 33.78 | 14.72 | 4.38 | 3.96 | 1.75 |
| KLF | 2 (0) | 873.79 | 857.24 | 867.73 | 49.11 | 33.90 | 43.88 | 5.62 | 3.95 | 5.06 |
| (58-40) | 2 (90) | 826.74 | 806.20 | 832.60 | 65.47 | 21.58 | 42.65 | 7.92 | 2.68 | 5.12 |
| (4.9%) | 3 (0) | 763.24 | 750.92 | 793.58 | 34.30 | 18.60 | 30.54 | 4.49 | 2.48 | 3.85 |
| | 3 (90) | 875.57 | 863.51 | 892.52 | 84.09 | 78.24 | 22.44 | 9.60 | 9.06 | 2.51 |

# APPENDIX B

## Resilient Modulus Test Results (25°C)

| Temp = 77F | | Res. Mod | | | Std. Dev. | | | Coeficient of Variance (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Freqency | ID (deg) | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 |
| GFC (4.5%) | 1 (0) | 251.85 | 242.58 | 234.73 | 18.19 | 7.13 | 7.13 | 7.22 | 2.94 | 3.04 |
| | 1 (90) | 239.87 | 221.38 | 221.83 | 3.21 | 8.78 | 4.67 | 1.34 | 3.97 | 2.11 |
| | 2 (0) | 238.41 | 242.51 | 239.24 | 7.54 | 3.55 | 7.70 | 3.16 | 1.46 | 3.22 |
| | 2 (90) | 233.54 | 233.72 | 239.04 | 4.71 | 4.76 | 3.51 | 2.02 | 2.04 | 1.47 |
| | 3 (0) | 270.17 | 271.58 | 274.13 | 8.46 | 1.79 | 4.08 | 3.13 | 0.66 | 1.49 |
| | 3 (90) | 277.64 | 261.67 | 249.85 | 19.82 | 12.84 | 9.61 | 7.14 | 4.91 | 3.84 |
| GFF (5.1%) | 1 (0) | 251.49 | 249.56 | 246.45 | 5.33 | 6.55 | 3.35 | 2.12 | 2.63 | 1.36 |
| | 1 (90) | 206.45 | 202.03 | 200.71 | 3.49 | 9.46 | 2.63 | 1.69 | 4.68 | 1.31 |
| | 2 (0) | 309.70 | 298.91 | 304.82 | 6.14 | 5.67 | 7.83 | 1.98 | 1.90 | 2.57 |
| | 2 (90) | 283.92 | 283.94 | 281.28 | 11.70 | 5.21 | 8.01 | 4.12 | 1.83 | 2.85 |
| | 3 (0) | 251.65 | 246.25 | 250.02 | 2.16 | 5.23 | 3.12 | 0.86 | 2.12 | 1.25 |
| | 3 (90) | 235.10 | 237.68 | 238.90 | 11.78 | 4.33 | 2.66 | 5.01 | 1.82 | 1.11 |
| NUC (4.7%) | 1 (0) | 188.03 | 189.26 | 186.30 | 2.87 | 2.83 | 3.48 | 1.53 | 1.49 | 1.87 |
| | 1 (90) | 199.29 | 205.21 | 199.97 | 15.44 | 5.61 | 2.26 | 7.75 | 2.73 | 1.13 |
| | 2 (0) | 220.47 | 223.47 | 222.45 | 3.69 | 4.13 | 7.91 | 1.67 | 1.85 | 3.56 |
| | 2 (90) | 257.63 | 243.91 | 244.77 | 5.45 | 10.31 | 5.95 | 2.12 | 4.23 | 2.43 |
| | 3 (0) | 217.12 | 215.11 | 217.56 | 2.16 | 4.42 | 2.96 | 0.99 | 2.05 | 1.36 |
| | 3 (90) | 259.61 | 247.39 | 249.13 | 15.88 | 7.03 | 1.53 | 6.12 | 2.84 | 0.61 |
| NUF (5.0%) | 1 (0) | 283.76 | 273.31 | 273.77 | 3.72 | 8.38 | 6.22 | 1.31 | 3.07 | 2.27 |
| | 1 (90) | 255.25 | 257.82 | 262.69 | 9.45 | 2.16 | 2.63 | 3.70 | 0.84 | 1.00 |
| | 2 (0) | 280.32 | 280.24 | 284.68 | 1.71 | 2.81 | 4.57 | 0.61 | 1.00 | 1.61 |
| | 2 (90) | 280.21 | 281.28 | 277.37 | 10.59 | 5.67 | 6.55 | 3.78 | 2.02 | 2.36 |
| | 3 (0) | 266.46 | 268.56 | 273.82 | 5.25 | 5.32 | 2.25 | 1.97 | 1.98 | 0.82 |
| | 3 (90) | 298.43 | 297.23 | 298.41 | 1.44 | 4.15 | 3.72 | 0.48 | 1.40 | 1.25 |
| KLC (4.4%) | 1 (0) | 335.25 | 338.88 | 334.55 | 8.34 | 5.40 | 4.25 | 2.49 | 1.59 | 1.27 |
| | 1 (90) | 314.42 | 315.10 | 316.09 | 6.83 | 29.69 | 4.97 | 2.17 | 9.42 | 1.57 |
| | 2 (0) | 339.71 | 344.83 | 349.74 | 6.98 | 7.17 | 7.74 | 2.05 | 2.08 | 2.21 |
| | 2 (90) | 311.06 | 306.02 | 311.30 | 7.13 | 7.19 | 5.47 | 2.29 | 2.35 | 1.76 |
| | 3 (0) | 303.25 | 310.25 | 310.72 | 4.05 | 9.20 | 10.65 | 1.34 | 2.97 | 3.43 |
| | 3 (90) | 327.45 | 310.00 | 312.61 | 22.22 | 7.69 | 6.95 | 6.79 | 2.48 | 2.22 |
| KLF (5.1%) | 1 (0) | 265.97 | 269.21 | 273.93 | 3.78 | 2.40 | 5.92 | 1.42 | 0.89 | 2.16 |
| | 1 (90) | 286.29 | 279.05 | 281.12 | 3.43 | 9.79 | 4.38 | 1.20 | 3.51 | 1.56 |
| | 2 (0) | 260.75 | 267.00 | 267.74 | 5.03 | 3.13 | 2.42 | 1.93 | 1.17 | 0.90 |
| | 2 (90) | 274.41 | 269.92 | 260.68 | 2.98 | 4.25 | 5.93 | 1.09 | 1.57 | 2.27 |
| | 3 (0) | 255.57 | 260.69 | 264.34 | 2.58 | 3.92 | 3.20 | 1.01 | 1.51 | 1.21 |
| | 3 (90) | 292.41 | 285.36 | 282.71 | 4.01 | 3.30 | 5.52 | 1.37 | 1.16 | 1.95 |
| CGC (4.6%) | 1 (0) | 274.65 | 269.23 | 265.69 | 3.24 | 5.88 | 2.83 | 1.18 | 2.19 | 1.07 |
| | 1 (90) | 279.13 | 281.54 | 281.14 | 10.41 | 6.73 | 8.29 | 3.73 | 2.39 | 2.95 |
| | 2 (0) | 296.50 | 286.83 | 274.82 | 3.82 | 2.55 | 7.39 | 1.29 | 0.89 | 2.69 |
| | 2 (90) | 293.97 | 293.03 | 287.49 | 5.63 | 5.61 | 1.26 | 1.91 | 1.91 | 0.44 |
| | 3 (0) | 252.81 | 246.89 | 245.83 | 7.00 | 4.59 | 6.36 | 2.77 | 1.86 | 2.59 |
| | 3 (90) | 238.98 | 241.08 | 241.47 | 11.65 | 1.27 | 1.71 | 4.87 | 0.53 | 0.71 |
| CGF (5.0%) | 1 (0) | 255.92 | 263.13 | 264.80 | 6.18 | 4.15 | 5.84 | 2.41 | 1.58 | 2.20 |
| | 1 (90) | 281.07 | 268.34 | 269.52 | 3.13 | 14.16 | 6.62 | 1.11 | 5.28 | 2.46 |
| | 2 (0) | 267.74 | 266.02 | 263.86 | 9.94 | 6.36 | 6.49 | 3.71 | 2.39 | 2.46 |
| | 2 (90) | 262.33 | 260.23 | 259.35 | 9.17 | 3.10 | 2.42 | 3.49 | 1.19 | 0.93 |
| | 3 (0) | 244.37 | 240.56 | 241.24 | 2.76 | 2.12 | 6.45 | 1.13 | 0.88 | 2.67 |
| | 3 (90) | 251.85 | 245.98 | 247.44 | 3.83 | 4.11 | 2.38 | 1.52 | 1.67 | 0.96 |
| NUF (58-40) (4.9%) | 1 (0) | 158.15 | 159.38 | 164.03 | 2.94 | 2.32 | 0.35 | 1.86 | 1.45 | 0.21 |
| | 1 (90) | 166.26 | 164.04 | 165.88 | 1.27 | 2.94 | 1.04 | 0.76 | 1.79 | 0.62 |
| | 2 (0) | 169.20 | 172.30 | 169.70 | 6.21 | 0.80 | 1.52 | 3.67 | 0.46 | 0.89 |
| | 2 (90) | 161.25 | 165.93 | 164.69 | 2.87 | 2.96 | 2.46 | 1.78 | 1.78 | 1.49 |
| | 3 (0) | 151.70 | 155.86 | 156.40 | 1.02 | 0.74 | 0.78 | 0.68 | 0.48 | 0.50 |
| | 3 (90) | 163.38 | 164.07 | 167.23 | 9.08 | 3.65 | 3.18 | 5.56 | 2.22 | 1.90 |
| KLF (58-40) (4.9%) | 1 (0) | 173.99 | 175.18 | 180.01 | 4.11 | 4.10 | 2.24 | 2.36 | 2.34 | 1.24 |
| | 1 (90) | 176.72 | 176.03 | 177.59 | 3.16 | 2.63 | 2.45 | 1.79 | 1.49 | 1.38 |
| | 2 (0) | 193.18 | 197.13 | 197.78 | 7.06 | 2.00 | 1.48 | 3.66 | 1.01 | 0.75 |
| | 2 (90) | 194.56 | 191.79 | 192.88 | 1.93 | 3.31 | 2.31 | 0.99 | 1.73 | 1.20 |
| | 3 (0) | 200.62 | 204.18 | 204.12 | 6.23 | 1.97 | 1.88 | 3.11 | 0.97 | 0.92 |
| | 3 (90) | 191.50 | 187.49 | 192.46 | 3.25 | 4.67 | 1.21 | 1.70 | 2.49 | 0.63 |

# APPENDIX B

## Resilient Modulus Test Results (40°C)

| Temp = 104F | | Res. Mod | | | Std. Dev. | | | Coeficient of Variance (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Freqency | ID (deg) | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 |
| GFC (4.5%) | 1 (0) | 63.86 | 61.74 | 60.36 | 6.83 | 3.89 | 1.93 | 10.70 | 6.30 | 3.20 |
| | 1 (90) | 62.96 | 56.42 | 56.59 | 6.72 | 3.77 | 2.04 | 10.68 | 6.68 | 3.60 |
| | 2 (0) | 69.09 | 64.05 | 65.62 | 3.70 | 2.61 | 2.27 | 5.35 | 4.07 | 3.45 |
| | 2 (90) | 67.14 | 62.59 | 65.17 | 8.96 | 6.19 | 1.60 | 13.34 | 9.89 | 2.46 |
| | 3 (0) | 71.51 | 66.77 | 64.68 | 5.93 | 4.57 | 4.86 | 8.29 | 6.84 | 7.51 |
| | 3 (90) | 67.80 | 69.41 | 65.82 | 6.29 | 3.37 | 1.34 | 9.28 | 4.85 | 2.03 |
| GFF (5.1%) | 1 (0) | 75.56 | 73.70 | 73.76 | 3.11 | 4.47 | 2.56 | 4.12 | 6.07 | 3.47 |
| | 1 (90) | 96.09 | 89.32 | 85.87 | 11.36 | 8.20 | 1.62 | 11.82 | 9.18 | 1.89 |
| | 2 (0) | 85.18 | 93.68 | 92.34 | 15.96 | 6.16 | 5.69 | 18.74 | 6.57 | 6.16 |
| | 2 (90) | 95.53 | 84.90 | 86.52 | 3.41 | 5.24 | 2.82 | 3.57 | 6.17 | 3.26 |
| | 3 (0) | 69.78 | 65.65 | 70.01 | 8.76 | 4.38 | 2.38 | 12.55 | 6.67 | 3.40 |
| | 3 (90) | 65.67 | 66.28 | 65.66 | 4.12 | 1.92 | 2.71 | 6.28 | 2.90 | 4.13 |
| NUC (4.7%) | 1 (0) | 60.77 | 62.52 | 59.66 | 6.57 | 1.06 | 1.08 | 10.81 | 1.70 | 1.81 |
| | 1 (90) | 46.44 | 46.71 | 46.26 | 1.69 | 1.22 | 1.01 | 3.64 | 2.62 | 2.19 |
| | 2 (0) | 81.52 | 62.21 | 71.67 | 2.11 | 27.65 | 1.50 | 2.58 | 44.44 | 2.09 |
| | 2 (90) | 76.29 | 67.69 | 67.42 | 1.72 | 2.33 | 2.18 | 2.26 | 3.44 | 3.23 |
| | 3 (0) | 76.87 | 72.81 | 70.83 | 5.70 | 2.74 | 2.31 | 7.42 | 3.76 | 3.26 |
| | 3 (90) | 75.46 | 68.25 | 69.09 | 8.60 | 4.33 | 2.46 | 11.40 | 6.34 | 3.56 |
| NUF (5.0%) | 1 (0) | 90.28 | 83.73 | 85.69 | 2.93 | 6.42 | 2.46 | 3.24 | 7.67 | 2.87 |
| | 1 (90) | 80.95 | 75.03 | 77.47 | 11.37 | 8.41 | 2.88 | 14.05 | 11.20 | 3.71 |
| | 2 (0) | 91.06 | 70.88 | 84.73 | 6.58 | 32.21 | 2.66 | 7.23 | 45.43 | 3.14 |
| | 2 (90) | 85.72 | 83.75 | 77.10 | 10.99 | 2.51 | 3.52 | 12.82 | 2.99 | 4.56 |
| | 3 (0) | 94.72 | 85.13 | 85.97 | 5.21 | 5.23 | 2.67 | 5.50 | 6.14 | 3.11 |
| | 3 (90) | 92.62 | 84.54 | 86.05 | 11.08 | 3.97 | 1.80 | 11.97 | 4.69 | 2.09 |
| KLC (4.4%) | 1 (0) | 112.32 | 105.64 | 105.66 | 13.94 | 4.44 | 4.64 | 12.41 | 4.20 | 4.39 |
| | 1 (90) | 89.56 | 92.57 | 95.18 | 6.15 | 2.71 | 4.78 | 6.87 | 2.93 | 5.02 |
| | 2 (0) | 115.08 | 111.49 | 108.85 | 7.78 | 8.49 | 5.28 | 6.76 | 7.61 | 4.85 |
| | 2 (90) | 119.82 | 102.29 | 100.72 | 8.97 | 5.89 | 4.20 | 7.49 | 5.76 | 4.17 |
| | 3 (0) | 112.73 | 106.52 | 102.64 | 9.28 | 3.47 | 4.85 | 8.24 | 3.26 | 4.72 |
| | 3 (90) | 112.37 | 98.18 | 100.83 | 7.65 | 5.49 | 5.92 | 6.81 | 5.59 | 5.87 |
| KLF (5.1%) | 1 (0) | 103.27 | 99.38 | 98.52 | 14.56 | 2.71 | 5.26 | 14.10 | 2.72 | 5.34 |
| | 1 (90) | 97.87 | 87.48 | 87.97 | 3.63 | 4.12 | 5.06 | 3.71 | 4.71 | 5.75 |
| | 2 (0) | 84.01 | 80.08 | 80.29 | 2.73 | 1.69 | 4.00 | 3.25 | 2.12 | 4.98 |
| | 2 (90) | 86.29 | 75.17 | 77.06 | 8.24 | 7.20 | 3.54 | 9.55 | 9.58 | 4.59 |
| | 3 (0) | 88.28 | 90.40 | 88.82 | 5.98 | 4.29 | 2.50 | 6.77 | 4.74 | 2.81 |
| | 3 (90) | 93.78 | 90.04 | 87.36 | 11.18 | 4.46 | 1.34 | 11.92 | 4.95 | 1.54 |
| CGC (4.6%) | 1 (0) | 89.48 | 85.11 | 84.09 | 7.67 | 4.22 | 1.52 | 8.58 | 4.96 | 1.81 |
| | 1 (90) | 88.65 | 80.71 | 79.87 | 5.71 | 3.68 | 3.07 | 6.44 | 4.56 | 3.84 |
| | 2 (0) | 89.88 | 83.63 | 82.81 | 2.86 | 2.51 | 2.84 | 3.18 | 3.00 | 3.43 |
| | 2 (90) | 93.86 | 87.11 | 79.64 | 1.88 | 1.46 | 2.98 | 2.00 | 1.68 | 3.75 |
| | 3 (0) | 75.22 | 70.99 | 68.91 | 2.21 | 2.24 | 1.68 | 2.94 | 3.16 | 2.43 |
| | 3 (90) | 72.32 | 69.62 | 62.23 | 9.31 | 2.98 | 3.59 | 12.88 | 4.27 | 5.76 |
| CGF (5.0%) | 1 (0) | 81.27 | 81.80 | 77.77 | 6.84 | 6.86 | 5.20 | 8.42 | 8.39 | 6.69 |
| | 1 (90) | 86.36 | 80.05 | 77.01 | 9.76 | 7.30 | 2.12 | 11.31 | 9.12 | 2.75 |
| | 2 (0) | 75.70 | 76.68 | 73.10 | 5.97 | 2.57 | 3.15 | 7.89 | 3.36 | 4.31 |
| | 2 (90) | 75.01 | 78.02 | 72.60 | 12.04 | 2.72 | 5.57 | 16.05 | 3.49 | 7.67 |
| | 3 (0) | 80.64 | 74.12 | 73.25 | 2.70 | 2.65 | 3.54 | 3.35 | 3.57 | 4.84 |
| | 3 (90) | 77.05 | 72.19 | 68.52 | 10.65 | 3.66 | 1.69 | 13.83 | 5.07 | 2.47 |
| KLF (58-40) (4.9%) | 1 (0) | 85.97 | 89.70 | 87.32 | 4.89 | 4.49 | 2.10 | 5.69 | 5.01 | 2.40 |
| | 1 (90) | 81.32 | 88.28 | 87.30 | 3.97 | 4.37 | 3.02 | 4.88 | 4.95 | 3.46 |
| | 2 (0) | 88.55 | 93.66 | 90.22 | 3.09 | 3.06 | 3.20 | 3.49 | 3.27 | 3.55 |
| | 2 (90) | 95.74 | 91.24 | 94.47 | 2.14 | 2.53 | 1.84 | 2.23 | 2.77 | 1.95 |
| | 3 (0) | 99.34 | 95.91 | 98.31 | 7.41 | 4.40 | 1.79 | 7.46 | 4.59 | 1.82 |
| | 3 (90) | 90.56 | 96.73 | 95.81 | 6.26 | 3.09 | 1.77 | 6.92 | 3.19 | 1.84 |
| NUF (58-40) (4.9%) | 1 (0) | 75.17 | 77.63 | 76.49 | 5.17 | 3.24 | 2.58 | 6.88 | 4.18 | 3.38 |
| | 1 (90) | 74.93 | 73.17 | 73.50 | 2.94 | 1.66 | 1.56 | 3.92 | 2.27 | 2.12 |
| | 2 (0) | 78.49 | 74.84 | 77.66 | 4.85 | 1.89 | 2.35 | 6.18 | 2.53 | 3.03 |
| | 2 (90) | 76.33 | 79.40 | 81.06 | 4.12 | 2.78 | 2.20 | 5.39 | 3.50 | 2.71 |
| | 3 (0) | 82.63 | 88.11 | 86.60 | 5.72 | 1.93 | 1.37 | 6.92 | 2.19 | 1.58 |
| | 3 (90) | 73.04 | 78.78 | 81.38 | 10.15 | 2.74 | 2.95 | 13.89 | 3.48 | 3.63 |

# APPENDIX C
# Moisture Sensitivity Results

GRANITE FALLS GRANITE

| Sample ID | Calculation | Item ID | GFC U1 | GFC U2 | GFC U3 | AVG | GFF U1 | GFF U2 | GFF U3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (in.) | | D | 5.84 | 5.80 | 5.77 | 5.80 | 5.84 | 5.92 | 5.86 | 5.87 |
| Diameter (mm) | | D | 14.84 | 14.72 | 14.67 | 14.74 | 14.85 | 15.03 | 14.89 | 14.92 |
| Thickness (cm) | | t | 8.42 | 8.41 | 8.47 | 8.43 | 8.53 | 8.22 | 8.34 | 8.36 |
| Dry Mass in Air (g) | | A | 3413.0 | 3388.6 | 3402.7 | 3401.4 | 3398.2 | 3421.8 | 3413.8 | 3411.3 |
| SSD Mass (g) | | B | 3439.1 | 3408.3 | 3421.8 | 3423.1 | 3416.6 | 3425.5 | 3417.3 | 3419.8 |
| Mass in Water (g) | | C | 1983.2 | 1977.3 | 1991.6 | 1984.0 | 1940.1 | 1968.0 | 1965.1 | 1957.7 |
| Volume | (B - C) | E | 1455.9 | 1431.0 | 1430.2 | 1439.0 | 1476.5 | 1457.5 | 1452.2 | 1462.1 |
| Bulk Specific Gravity | (A / E) | F | 2.344 | 2.368 | 2.379 | 2.364 | 2.302 | 2.348 | 2.351 | 2.333 |
| Max Specific Gravity | | G | 2.533 | 2.528 | 2.528 | 2.530 | 2.500 | 2.505 | 2.505 | 2.503 |
| % Air Voids | (100*(G-F)/G) | H | 7.45 | 6.33 | 5.89 | 6.56 | 7.94 | 6.28 | 6.16 | 6.79 |
| Volume of Air Voids | (H*E/100) | I | 108.49 | 90.57 | 84.20 | 94.42 | 117.22 | 91.51 | 89.41 | 99.38 |
| Load (lbf) | | P | 4997.0 | 4987.0 | 4981.0 | 4988.3 | 4981.3 | 4966.0 | 4965.0 | 4970.8 |

| Sample ID | Calculation | Item ID | GFC U1 | GFC C2 | GFC C3 | AVG | GFF C1 | GFF C2 | GFF C3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (mm) | | D | 14.99 | 14.87 | 14.78 | 14.88 | 15.05 | 15.05 | 15.07 | 15.06 |
| Thickness (cm) | | t | 8.21 | 8.28 | 8.34 | 8.28 | 8.25 | 8.25 | 8.02 | 8.18 |
| Dry Mass in Air (g) | | A | 3406.3 | 3390.8 | 3406.8 | 3401.3 | 3388.0 | 3401.8 | 3369.2 | 3386.3 |
| SSD Mass (g) | | B | 3429.4 | 3420.6 | 3424.5 | 3424.8 | 3404.4 | 3418.3 | 3374.0 | 3398.9 |
| Mass in Water (g) | | C | 1980.9 | 1981.6 | 1993.4 | 1985.3 | 1935.6 | 1950.3 | 1943.7 | 1943.2 |
| Volume | (B - C) | E | 1448.5 | 1439.0 | 1431.1 | 1439.5 | 1468.8 | 1468.0 | 1430.3 | 1455.7 |
| Bulk Specific Gravity | (A / E) | F | 2.352 | 2.356 | 2.381 | 2.363 | 2.307 | 2.317 | 2.356 | 2.326 |
| Max Specific Gravity | | G | 2.533 | 2.533 | 2.528 | 2.531 | 2.500 | 2.500 | 2.505 | 2.502 |
| % Air Voids | (100*(G-F)/G) | H | 7.16 | 6.97 | 5.83 | 6.66 | 7.73 | 7.31 | 5.96 | 7.01 |
| Volume of Air Voids | (H*E/100) | I | 103.73 | 100.35 | 83.47 | 95.85 | 113.60 | 107.28 | 85.31 | 102.07 |
| Load (lbf) | | P | 4978.9 | 4975.5 | 4975.8 | 4976.7 | 4983.4 | 4982.3 | 4978.2 | 4981.3 |
| **Vacuum Saturated at 25 in. Hg for 5-25 min** | | | | | | | | | | |
| SSD Mass | | B' | 3475.5 | 3462.0 | 3463.1 | 3466.9 | 3467.8 | 3476.4 | 3427.3 | 3457.2 |
| Mass in Water | | C' | 1974.6 | 1974.6 | 1985.5 | 1978.2 | 1928.8 | 1947.9 | 1938.8 | 1938.5 |
| Volume | (B'-C') | E' | 1500.93 | 1487.43 | 1477.58 | 1488.65 | 1538.95 | 1528.49 | 1488.47 | 1518.64 |
| Vol Abs Water | (B'-A) | J' | 69.20 | 71.20 | 56.30 | 65.57 | 79.80 | 74.60 | 58.10 | 70.83 |
| % Saturation | (100*J'/I) | | 66.71 | 70.95 | 67.45 | 68.37 | 70.25 | 69.54 | 68.10 | 69.30 |
| % Swell | (100*(E'-E)/E) | | 3.62 | 3.37 | 3.25 | 3.41 | 4.78 | 4.12 | 4.07 | 4.32 |
| **Conditioned 24 hours in 140 Deg Water Bath** | | | | | | | | | | |
| Diameter | | D' | 15.07 | 15.00 | 15.09 | 15.05 | 15.06 | 15.04 | 15.04 | 15.05 |
| Thickness (cm) | | t" | 8.46 | 8.54 | 8.45 | 8.48 | 8.40 | 8.44 | 8.36 | 8.40 |
| SSD Mass | | B" | 3487.0 | 3493.3 | 3473.4 | 3484.6 | 3481.0 | 3493.5 | 3493.7 | 3489.4 |
| Mass in Water | | C" | 1977.9 | 1985.0 | 1963.1 | 1975.3 | 1926.0 | 1946.3 | 1937.2 | 1936.5 |
| Volume | (B"-C") | E" | 1509.1 | 1508.3 | 1510.3 | 1509.2 | 1555.0 | 1547.2 | 1556.5 | 1552.9 |
| Vol Abs Water | (B"-A) | J" | 80.70 | 102.50 | 66.60 | 83.27 | 93.00 | 91.70 | 124.50 | 103.07 |
| % Saturation | (100*J"/I) | | 77.80 | 102.14 | 79.79 | 86.58 | 81.87 | 85.48 | 145.94 | 104.43 |
| % Swell | (100*(E"-E)/E) | | 4.18 | 4.81 | 5.54 | 4.84 | 5.87 | 5.40 | 8.82 | 6.70 |
| Load (lbf) | | P" | 4978.9 | 4975.5 | 4975.8 | 4976.7 | 4983.4 | 4982.3 | 4978.2 | 4981.3 |
| Dry Strength | (2000*P/(pi*t*D)) | Sd | 25467.7 | 25768.9 | 25722.0 | 25652.8 | 25523.3 | 25451.8 | 26152.8 | 25709.3 |
| Wet Strength | (2000*P"/(pi*t"*D')) | Sw | 24859.8 | 24734.5 | 24849.1 | 24814.5 | 25079.5 | 24999.1 | 25212.9 | 25097.2 |
| TSR | (100*(Sw/Sd)) | | | | | 96.7 | | | | 97.6 |

# APPENDIX C
## Moisture Sensitivity Results

NEW ULM QUARTZITE

| Sample ID | Calculation | Item ID | NUC U1 | NUC U2 | NUC U3 | AVG | NUF U1 | NUF U2 | NUF U3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (in.) | | *D* | 5.79 | 5.81 | 5.82 | 5.81 | 5.84 | 5.82 | 5.85 | 5.84 |
| Diameter (mm) | | *D* | 14.70 | 14.77 | 14.77 | 14.75 | 14.85 | 14.78 | 14.86 | 14.83 |
| Thickness (cm) | | *t* | 8.60 | 8.58 | 8.47 | 8.55 | 8.49 | 8.50 | 8.45 | 8.48 |
| Dry Mass in Air (g) | | *A* | 3406.2 | 3411.5 | 3400.9 | 3406.2 | 3388.0 | 3399.5 | 3411.4 | 3399.6 |
| SSD Mass (g) | | *B* | 3425.8 | 3445.3 | 3418.7 | 3429.9 | 3404.4 | 3409.8 | 3416.3 | 3410.2 |
| Mass in Water (g) | | *C* | 1967.0 | 1975.6 | 1967.2 | 1969.9 | 1935.6 | 1951.7 | 1951.6 | 1946.3 |
| Volume | *(B - C)* | *E* | 1458.8 | 1469.7 | 1451.5 | 1460.0 | 1468.8 | 1458.1 | 1464.7 | 1463.9 |
| Bulk Specific Gravity | *(A / E)* | *F* | 2.335 | 2.321 | 2.343 | 2.333 | 2.307 | 2.331 | 2.329 | 2.322 |
| Max Specific Gravity | | *G* | 2.498 | 2.506 | 2.506 | 2.503 | 2.504 | 2.511 | 2.511 | 2.509 |
| % Air Voids | *(100*(G-F)/G)* | *H* | 6.53 | 7.37 | 6.50 | 6.80 | 7.88 | 7.15 | 7.25 | 7.43 |
| Volume of Air Voids | *(H*E/100)* | *I* | 95.23 | 108.37 | 94.40 | 99.33 | 115.76 | 104.26 | 106.12 | 108.71 |
| Load (lbf) | | *P* | 4970.0 | 4965.2 | 4963.5 | 4966.2 | 4962.0 | 4966.0 | 4909.0 | 4945.7 |

| Sample ID | Calculation | Item ID | NUC C1 | NUC C2 | NUC C3 | AVG | NUF C1 | NUF C2 | NUF C3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (mm) | | *D* | 14.77 | 14.89 | 14.68 | 14.78 | 14.96 | 14.96 | 14.95 | 14.95 |
| Thickness (cm) | | *t* | 8.55 | 8.41 | 8.61 | 8.53 | 8.39 | 8.11 | 8.30 | 8.27 |
| Dry Mass in Air (g) | | *A* | 3415.1 | 3412.1 | 3403.4 | 3410.2 | 3400.4 | 3286.3 | 3404.2 | 3363.6 |
| SSD Mass (g) | | *B* | 3434.7 | 3440.8 | 3432.2 | 3435.9 | 3417.0 | 3304.6 | 3404.6 | 3375.4 |
| Mass in Water (g) | | *C* | 1970.1 | 1976.5 | 1974.6 | 1973.7 | 1941.7 | 1879.8 | 1947.3 | 1922.9 |
| Volume | *(B - C)* | *E* | 1464.6 | 1464.3 | 1457.6 | 1462.2 | 1475.3 | 1424.8 | 1457.3 | 1452.5 |
| Bulk Specific Gravity | *(A / E)* | *F* | 2.332 | 2.330 | 2.335 | 2.332 | 2.305 | 2.306 | 2.336 | 2.316 |
| Max Specific Gravity | | *G* | 2.498 | 2.498 | 2.506 | 2.501 | 2.504 | 2.504 | 2.511 | 2.506 |
| % Air Voids | *(100*(G-F)/G)* | *H* | 6.65 | 6.72 | 6.83 | 6.73 | 7.95 | 7.89 | 6.97 | 7.60 |
| Volume of Air Voids | *(H*E/100)* | *I* | 97.47 | 98.37 | 99.50 | 98.45 | 117.31 | 112.38 | 101.59 | 110.41 |
| Load (lbf) | | *P* | 4975.1 | 4970.3 | 4968.3 | 4971.2 | 4980.6 | 4962.8 | 4972.4 | 4971.9 |
| **Vacuum Saturated at 25 in. Hg for 5-25 min** | | | | | | | | | | |
| SSD Mass | | *B'* | 3483.8 | 3481.0 | 3470.7 | 3478.5 | 3477.5 | 3360.8 | 3473.5 | 3437.3 |
| Mass in Water | | *C'* | 1961.1 | 1963.3 | 1958.6 | 1961.0 | 1945.8 | 1881.8 | 1959.3 | 1929.0 |
| Volume | *(B'-C')* | *E'* | 1522.71 | 1517.67 | 1512.13 | 1517.50 | 1531.68 | 1478.98 | 1514.20 | 1508.29 |
| Vol Abs Water | *(B'-A)* | *J'* | 68.70 | 68.90 | 67.30 | 68.30 | 77.10 | 74.50 | 69.30 | 73.63 |
| % Saturation | *(100*J'/I)* | | 70.49 | 70.04 | 67.64 | 69.39 | 65.72 | 66.29 | 68.22 | 66.74 |
| % Swell | *(100*(E'-E)/E)* | | 3.97 | 3.65 | 3.74 | 3.78 | 3.82 | 3.80 | 3.90 | 3.84 |
| **Conditioned 24 hours in 140 Deg Water Bath** | | | | | | | | | | |
| Diameter | | *D'* | 15.04 | 15.05 | 15.07 | 15.05 | 15.05 | 15.03 | 15.05 | 15.04 |
| Thickness (cm) | | *t"* | 8.69 | 8.59 | 8.65 | 8.64 | 8.46 | 8.21 | 8.40 | 8.36 |
| SSD Mass | | *B"* | 3494.8 | 3491.8 | 3480.2 | 3488.9 | 3492.2 | 3377.1 | 3492.8 | 3454.0 |
| Mass in Water | | *C"* | 1951.1 | 1964.3 | 1937.2 | 1950.9 | 1944.3 | 1880.3 | 1958.5 | 1927.7 |
| Volume | *(B"-C")* | *E"* | 1543.7 | 1527.5 | 1543.0 | 1538.1 | 1547.9 | 1496.8 | 1534.3 | 1526.3 |
| Vol Abs Water | *(B"-A)* | *J"* | 79.70 | 79.70 | 76.80 | 78.73 | 91.80 | 90.80 | 88.60 | 90.40 |
| % Saturation | *(100*J"/I)* | | 81.77 | 81.02 | 77.19 | 79.99 | 78.25 | 80.80 | 87.22 | 82.09 |
| % Swell | *(100*(E"-E)/E)* | | 5.40 | 4.32 | 5.86 | 5.19 | 4.92 | 5.05 | 5.28 | 5.09 |
| Load (lbf) | | *P"* | 4975.1 | 4970.3 | 4968.3 | 4971.2 | 4980.6 | 4962.8 | 4972.4 | 4971.9 |
| Dry Strength | *(2000*P/(pi*t*D))* | *Sd* | 25055.2 | 25238.7 | 24993.5 | 25095.8 | 25161.4 | 26062.1 | 25175.3 | 25466.3 |
| Wet Strength | *(2000*P"/(pi*t"*D'))* | *Sw* | 24236.2 | 24480.7 | 24261.1 | 24326.0 | 24901.9 | 25598.7 | 25045.4 | 25182.0 |
| TSR | *(100*(Sw/Sd))* | | | | | 96.9 | | | | 98.9 |

# APPENDIX C
## Moothing Sensitivity Results

KASOTA LIMESTONE

| Sample ID | Calculation | Item ID | KLC U1 | KLC U2 | KLC U3 | AVG | KLF U1 | KLF U2 | KLF U3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (in.) | | D | 5.82 | 5.76 | 5.75 | 5.78 | 5.87 | 5.88 | | 5.88 |
| Diameter (mm) | | D | 14.80 | 14.64 | 14.60 | 14.68 | 14.91 | 14.94 | | 14.93 |
| Thickness (cm) | | t | 8.46 | 8.66 | 8.75 | 8.62 | 8.44 | 8.34 | | 8.39 |
| Dry Mass in Air (g) | | A | 3402.8 | 3410.4 | 3395.5 | 3402.9 | 3407.1 | 3414.5 | | 3410.8 |
| SSD Mass (g) | | B | 3423.2 | 3434.9 | 3439.0 | 3432.4 | 3411.7 | 3418.1 | | 3414.9 |
| Mass in Water (g) | | C | 1968.6 | 1978.3 | 1974.0 | 1973.6 | 1938.5 | 1954.7 | | 1946.6 |
| Volume | (B - C) | E | 1454.6 | 1456.6 | 1465.0 | 1458.7 | 1473.2 | 1463.4 | | 1468.3 |
| Bulk Specific Gravity | (A / E) | F | 2.339 | 2.341 | 2.318 | 2.333 | 2.313 | 2.333 | | 2.323 |
| Max Specific Gravity | | G | 2.501 | 2.501 | 2.504 | 2.502 | 2.489 | 2.487 | | 2.488 |
| % Air Voids | (100*(G-F)/G) | H | 6.46 | 6.38 | 7.44 | 6.76 | 7.08 | 6.18 | | 6.63 |
| Volume of Air Voids | (H*E/100) | I | 94.02 | 92.99 | 108.97 | 98.6598 | 104.34 | 90.46 | | 97.40 |
| Load (lbf) | | P | 4960.0 | 4959.7 | 4956.9 | 4958.9 | 4958.0 | 4956.0 | | 4957.0 |

| Sample ID | Calculation | Item ID | KLC C1 | KLC C2 | KLC C3 | AVG | KLF C1 | KLF C2 | KLF C3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (mm) | | D | 14.77 | 14.72 | 14.75 | 14.75 | 15.01 | 15.11 | 15.08 | 15.07 |
| Thickness (cm) | | t | 8.52 | 8.60 | 8.49 | 8.53 | 8.32 | 8.11 | 8.06 | 8.16 |
| Dry Mass in Air (g) | | A | 3407.9 | 3403.3 | 3395.2 | 3402.1 | 3405.2 | 3394.2 | 3358.4 | 3385.9 |
| SSD Mass (g) | | B | 3434.7 | 3442.0 | 3425.5 | 3434.1 | 3410.1 | 3398.8 | 3363.2 | 3390.7 |
| Mass in Water (g) | | C | 1975.6 | 1978.3 | 1974.6 | 1976.2 | 1936.9 | 1945.1 | 1925.0 | 1935.7 |
| Volume | (B - C) | E | 1459.1 | 1463.7 | 1450.9 | 1457.9 | 1473.2 | 1453.7 | 1438.2 | 1455.0 |
| Bulk Specific Gravity | (A / E) | F | 2.336 | 2.325 | 2.340 | 2.334 | 2.311 | 2.335 | 2.335 | 2.327 |
| Max Specific Gravity | | G | 2.501 | 2.504 | 2.504 | 2.503 | 2.489 | 2.487 | 2.487 | 2.488 |
| % Air Voids | (100*(G-F)/G) | H | 6.61 | 7.14 | 6.55 | 6.77 | 7.13 | 6.12 | 6.11 | 6.46 |
| Volume of Air Voids | (H*E/100) | I | 96.49 | 104.55 | 94.99 | 98.68 | 105.10 | 88.92 | 87.82 | 93.95 |
| Load (lbf) | | P | 4958.0 | 4957.3 | 4956.9 | 4957.4 | 4999.8 | 4996.4 | 4992.3 | 4996.2 |
| Vacuum Saturated at 25 in. Hg for 5-25 min | | | | | | | | | | |
| SSD Mass | | B' | 3475.6 | 3479.8 | 3462.9 | 3472.8 | 3473.1 | 3443.6 | 3408.9 | 3441.9 |
| Mass in Water | | C' | 1973.8 | 1966.1 | 1972.1 | 1970.7 | 1938.8 | 1957.6 | 1932.3 | 1942.9 |
| Volume | (B'-C') | E' | 1501.77 | 1513.72 | 1490.78 | 1502.09 | 1534.28 | 1486.02 | 1476.59 | 1498.96 |
| Vol Abs Water | (B'-A) | J' | 67.70 | 76.50 | 67.70 | 70.63 | 67.90 | 49.40 | 50.50 | 55.93 |
| % Saturation | (100*J'/I) | | 70.17 | 73.17 | 71.27 | 71.53 | 64.60 | 55.55 | 57.51 | 59.22 |
| % Swell | (100*(E'-E)/E) | | 2.92 | 3.42 | 2.75 | 3.03 | 4.15 | 2.22 | 2.67 | 3.01 |
| Conditioned 24 hours in 140 Deg Water Bath | | | | | | | | | | |
| Diameter | | D' | 15.09 | 15.06 | 15.06 | 15.07 | 15.05 | 15.21 | 15.03 | 15.10 |
| Thickness (cm) | | t" | 8.64 | 8.65 | 8.52 | 8.60 | 8.43 | 8.27 | 8.21 | 8.31 |
| SSD Mass | | B" | 3505.5 | 3507.9 | 3488.6 | 3500.7 | 3495.7 | 3457.9 | 3428.6 | 3460.7 |
| Mass in Water | | C" | 1959.6 | 1967.3 | 1970.4 | 1965.8 | 1937.6 | 1956.7 | 1931.4 | 1941.9 |
| Volume | (B"-C") | E" | 1545.9 | 1540.6 | 1518.2 | 1534.9 | 1558.1 | 1501.2 | 1497.2 | 1518.8 |
| Vol Abs Water | (B"-A) | J" | 97.60 | 104.60 | 93.40 | 98.53 | 90.50 | 63.70 | 70.20 | 74.80 |
| % Saturation | (100*J"/I) | | 101.16 | 100.04 | 98.33 | 99.84 | 86.11 | 71.63 | 79.94 | 79.23 |
| % Swell | (100*(E"-E)/E) | | 5.95 | 5.25 | 4.64 | 5.28 | 5.76 | 3.27 | 4.10 | 4.38 |
| Load (lbf) | | P" | 4958.0 | 4957.3 | 4956.9 | 4957.4 | 4999.8 | 4996.4 | 4992.3 | 4996.2 |
| Dry Strength | (2000*P/(pi*t*D)) | Sd | 25105.2 | 24942.3 | 25200.5 | 25082.7 | 25263.5 | 25753.6 | | 25508.5 |
| Wet Strength | (2000*P"/(pi*t"*D')) | Sw | 24202.2 | 24229.5 | 24537.9 | 24323.2 | 25080.8 | 25275.4 | 25756.0 | 25370.7 |
| TSR | (100*(Sw/Sd)) | | | | | 97.0 | | | | 99.5 |

# APPENDIX C
## Moisture Sensitivity Results

| | | | CEDAR GROVE GRAVEL | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample ID | Calculation | Item ID | CGC U1 | CGC U2 | CGC U3 | AVG | CGF U1 | CGF U2 | CGF U3 | AVG |
| Diameter (in.) | | D | 5.79 | 5.78 | 5.81 | 5.79 | 5.86 | 5.86 | 5.86 | 5.86 |
| Diameter (mm) | | D | 14.71 | 14.68 | 14.76 | 14.71 | 14.89 | 14.88 | 14.89 | 14.89 |
| Thickness (cm) | | t | 8.56 | 8.59 | 8.46 | 8.54 | 8.33 | 8.28 | 8.37 | 8.33 |
| Dry Mass in Air (g) | | A | 3394.1 | 3406.1 | 3397.7 | 3399.3 | 3394.6 | 3383.3 | 3384.6 | 3387.5 |
| SSD Mass (g) | | B | 3430.8 | 3432.6 | 3421.1 | 3428.2 | 3400.5 | 3387.7 | 3390.8 | 3393.0 |
| Mass in Water (g) | | C | 1977.6 | 1980.0 | 1973.5 | 1977.0 | 1950.6 | 1947.6 | 1934.1 | 1944.1 |
| Volume | (B - C) | E | 1453.2 | 1452.6 | 1447.6 | 1451.1 | 1449.9 | 1440.1 | 1456.7 | 1448.9 |
| Bulk Specific Gravity | (A / E) | F | 2.336 | 2.345 | 2.347 | 2.343 | 2.341 | 2.349 | 2.323 | 2.338 |
| Max Specific Gravity | | G | 2.512 | 2.510 | 2.510 | 2.511 | 2.525 | 2.525 | 2.502 | 2.517 |
| % Air Voids | (100*(G-F)/G) | H | 7.02 | 6.58 | 6.49 | 6.70 | 7.28 | 6.96 | 7.12 | 7.12 |
| Volume of Air Voids | (H*E/100) | I | 102.05 | 95.59 | 93.93 | 97.19 | 105.50 | 100.18 | 103.67 | 103.12 |
| Load (lbf) | | P | 4989.2 | 4978.2 | 4974.4 | 4980.6 | 4967.0 | 4959.0 | 4962.0 | 4962.7 |

| Sample ID | Calculation | Item ID | CGC C1 | CGC C2 | CGC C3 | AVG | CGF C1 | CGF C2 | CGF C3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (mm) | | D | 14.91 | 14.92 | 14.77 | 14.87 | 15.02 | 15.00 | 15.01 | 15.01 |
| Thickness (cm) | | t | 8.36 | 8.33 | 8.46 | 8.38 | 8.14 | 8.26 | 8.25 | 8.22 |
| Dry Mass in Air (g) | | A | 3422.0 | 3413.2 | 3400.2 | 3411.8 | 3394.5 | 3379.7 | 3379.4 | 3384.5 |
| SSD Mass (g) | | B | 3447.6 | 3437.0 | 3421.3 | 3435.3 | 3401.2 | 3385.5 | 3384.4 | 3390.4 |
| Mass in Water (g) | | C | 1987.2 | 1981.3 | 1970.6 | 1979.7 | 1959.2 | 1925.3 | 1925.4 | 1936.6 |
| Volume | (B - C) | E | 1460.4 | 1455.7 | 1450.7 | 1455.6 | 1442.0 | 1460.2 | 1459.0 | 1453.7 |
| Bulk Specific Gravity | (A / E) | F | 2.343 | 2.345 | 2.344 | 2.344 | 2.354 | 2.315 | 2.316 | 2.328 |
| Max Specific Gravity | | G | 2.512 | 2.512 | 2.510 | 2.511 | 2.502 | 2.525 | 2.525 | 2.517 |
| % Air Voids | (100*(G-F)/G) | H | 6.72 | 6.66 | 6.62 | 6.67 | 5.91 | 8.33 | 8.27 | 7.51 |
| Volume of Air Voids | (H*E/100) | I | 98.14 | 96.94 | 96.04 | 97.04 | 85.29 | 121.70 | 120.62 | 109.24 |
| Load (lbf) | | P | 4955.9 | 4950.1 | 5009.1 | 4971.7 | 4973.1 | 4975.5 | 4971.0 | 4973.2 |
| Vacuum Saturated at 25 in. Hg for 5-25 min | | | | | | | | | | |
| SSD Mass | | B' | 3491.2 | 3480.3 | 3467.3 | 3479.6 | 3456.5 | 3463.4 | 3462.9 | 3460.9 |
| Mass in Water | | C' | 1983.5 | 1978.1 | 1965.6 | 1975.7 | 1954.9 | 1940.8 | 1925.5 | 1940.4 |
| Volume | (B'-C') | E' | 1507.72 | 1502.15 | 1501.70 | 1503.86 | 1501.61 | 1522.56 | 1537.42 | 1520.53 |
| Vol Abs Water | (B'-A) | J' | 69.20 | 67.10 | 67.10 | 67.80 | 62.00 | 83.70 | 83.50 | 76.40 |
| % Saturation | (100*J'/I) | | 70.51 | 69.22 | 69.87 | 69.87 | 72.70 | 68.77 | 69.22 | 70.23 |
| % Swell | (100*(E'-E)/E) | | 3.24 | 3.19 | 3.52 | 3.32 | 4.13 | 4.27 | 5.38 | 4.59 |
| Conditioned 24 hours in 140 Deg Water Bath | | | | | | | | | | |
| Diameter | | D' | 15.14 | 15.08 | 15.08 | 15.10 | 15.04 | 15.01 | 15.06 | 15.04 |
| Thickness (cm) | | t" | 8.50 | 8.48 | 8.48 | 8.49 | 8.30 | 8.40 | 8.39 | 8.36 |
| SSD Mass | | B" | 3507.8 | 3496.5 | 3483.5 | 3495.9 | 3468.2 | 3479.0 | 3475.5 | 3474.2 |
| Mass in Water | | C" | 1977.4 | 1981.9 | 1969.6 | 1976.3 | 1953.7 | 1939.6 | 1924.8 | 1939.4 |
| Volume | (B"-C") | E" | 1530.4 | 1514.6 | 1513.9 | 1519.6 | 1514.5 | 1539.4 | 1550.7 | 1534.9 |
| Vol Abs Water | (B"-A) | J" | 85.80 | 83.30 | 83.30 | 84.13 | 73.70 | 99.30 | 96.10 | 89.70 |
| % Saturation | (100*J"/I) | | 87.43 | 85.93 | 86.74 | 86.70 | 86.42 | 81.59 | 79.67 | 82.56 |
| % Swell | (100*(E"-E)/E) | | 4.79 | 4.05 | 4.36 | 4.40 | 5.03 | 5.42 | 6.29 | 5.58 |
| Load (lbf) | | P" | 4955.9 | 4950.1 | 5009.1 | 4971.7 | 4973.1 | 4975.5 | 4971.0 | 4973.2 |
| Dry Strength | (2000*P/(pi*t*D)) | Sd | 25471.1 | 25504.7 | 25331.7 | 25435.8 | 25860.4 | 25474.4 | 25516.8 | 25617.2 |
| Wet Strength | (2000*P"/(pi*t"*D')) | Sw | 24511.3 | 24641.1 | 24946.6 | 24699.7 | 25357.2 | 25108.5 | 25046.8 | 25170.8 |
| TSR | (100*(Sw/Sd)) | | | | | 97.1 | | | | 98.3 |

# APPENDIX C
## Moisture Sensitivity Results

NEW ULM AND KASOTA (PG 58-40 MIXES)

| Sample ID | Calculation | Item ID | NUF U1 | NUF U2 | NUF U3 | AVG | KLF U1 | KLF U2 | KLF U3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (in.) | | D | 5.84 | 5.84 | 5.80 | 5.83 | 5.88 | 5.87 | 5.93 | 5.89 |
| Diameter (mm) | | D | 14.83 | 14.84 | 14.74 | 14.80 | 14.94 | 14.92 | 15.06 | 14.97 |
| Thickness (cm) | | t | 8.44 | 8.36 | 8.53 | 8.44 | 8.37 | 8.29 | 8.38 | 8.34 |
| Dry Mass in Air (g) | | A | 3398.8 | 3367.3 | 3399.8 | 3388.6 | 3406.0 | 3367.0 | 3415.9 | 3396.3 |
| SSD Mass (g) | | B | 3407.9 | 3378.4 | 3407.2 | 3397.8 | 3415.3 | 3377.6 | 3429.3 | 3407.4 |
| Mass in Water (g) | | C | 1949.5 | 1933.4 | 1951.4 | 1944.8 | 1948.2 | 1928.5 | 1938.2 | 1938.3 |
| Volume | (B - C) | E | 1458.4 | 1445.0 | 1455.8 | 1453.1 | 1467.1 | 1449.1 | 1491.1 | 1469.1 |
| Bulk Specific Gravity | (A / E) | F | 2.330 | 2.330 | 2.335 | 2.332 | 2.322 | 2.324 | 2.291 | 2.312 |
| Max Specific Gravity | | G | 2.499 | 2.504 | 2.504 | 2.502 | 2.491 | 2.491 | 2.493 | 2.492 |
| % Air Voids | (100*(G-F)/G) | H | 6.74 | 6.94 | 6.74 | 6.80 | 6.80 | 6.72 | 8.11 | 7.21 |
| Volume of Air Voids | (H*E/100) | I | 98.34 | 100.23 | 98.05 | 98.87 | 99.78 | 97.43 | 120.90 | 106.04 |
| Load (lbf) | | P | 4967.0 | 4967.0 | 4968.0 | 4967.3 | 4959.0 | 4960.0 | 4954.0 | 4957.7 |

| Sample ID | Calculation | Item ID | NUF C1 | NUF C2 | NUF C3 | AVG | KLF C1 | KLF C2 | KLF C3 | AVG |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter (mm) | | D | 14.90 | 14.93 | 14.79 | 14.87 | 14.93 | 14.83 | 14.83 | 14.86 |
| Thickness (cm) | | t | 8.38 | 8.38 | 8.47 | 8.41 | 8.36 | 8.58 | 8.56 | 8.50 |
| Dry Mass in Air (g) | | A | 3394.2 | 3418.5 | 3403.4 | 3405.4 | 3412.5 | 3404.1 | 3400.5 | 3405.7 |
| SSD Mass (g) | | B | 3404.0 | 3428.1 | 3411.6 | 3414.6 | 3422.2 | 3419.7 | 3415.4 | 3419.1 |
| Mass in Water (g) | | C | 1941.3 | 1960.3 | 1957.4 | 1953.0 | 1957.4 | 1937.1 | 1937.4 | 1944.0 |
| Volume | (B - C) | E | 1462.7 | 1467.8 | 1454.2 | 1461.6 | 1464.8 | 1482.6 | 1478.0 | 1475.1 |
| Bulk Specific Gravity | (A / E) | F | 2.321 | 2.329 | 2.340 | 2.330 | 2.330 | 2.296 | 2.301 | 2.309 |
| Max Specific Gravity | | G | 2.499 | 2.499 | 2.504 | 2.501 | 2.491 | 2.493 | 2.493 | 2.492 |
| % Air Voids | (100*(G-F)/G) | H | 7.14 | 6.80 | 6.53 | 6.83 | 6.48 | 7.90 | 7.71 | 7.37 |
| Volume of Air Voids | (H*E/100) | I | 104.48 | 99.85 | 95.01 | 99.78 | 94.87 | 117.14 | 113.98 | 108.66 |
| Load (lbf) | | P | 4967.2 | 4972.4 | 4961.1 | 4966.9 | 4969.0 | 4961.7 | 4970.0 | 4966.9 |
| **Vacuum Saturated at 25 in. Hg for 5-25 min** | | | | | | | | | | |
| SSD Mass | | B' | 3468.6 | 3486.7 | 3468.2 | 3474.5 | 3486.1 | 3492.2 | 3488.2 | 3488.8 |
| Mass in Water | | C' | 1945.2 | 1971.6 | 1967.3 | 1961.3 | 1972.7 | 1945.1 | 1949.4 | 1955.8 |
| Volume | (B'-C') | E' | 1523.44 | 1515.07 | 1500.94 | 1513.15 | 1513.41 | 1547.06 | 1538.77 | 1533.08 |
| Vol Abs Water | (B'-A) | J' | 74.40 | 68.20 | 64.80 | 69.13 | 73.60 | 88.10 | 87.70 | 83.13 |
| % Saturation | (100*J'/I) | | 71.21 | 68.30 | 68.20 | 69.24 | 77.58 | 75.21 | 76.94 | 76.58 |
| % Swell | (100*(E'-E)/E) | | 4.15 | 3.22 | 3.21 | 3.53 | 3.32 | 4.35 | 4.11 | 3.93 |
| **Conditioned 24 hours in 140 Deg Water Bath** | | | | | | | | | | |
| Diameter | | D" | 15.08 | 15.04 | 15.05 | 15.06 | 15.05 | 15.09 | 15.09 | 15.07 |
| Thickness (cm) | | t" | 8.38 | 8.44 | 8.35 | 8.39 | 8.40 | 8.52 | 8.49 | 8.47 |
| SSD Mass | | B" | 3488.7 | 3508.8 | 3485.6 | 3494.4 | 3518.1 | 3528.8 | 3522.7 | 3523.2 |
| Mass in Water | | C" | 1944.8 | 1971.1 | 1966.3 | 1960.7 | 1971.9 | 1944.6 | 1948.5 | 1955.0 |
| Volume | (B"-C") | E" | 1543.9 | 1537.7 | 1519.3 | 1533.6 | 1546.2 | 1584.2 | 1574.2 | 1568.2 |
| Vol Abs Water | (B"-A) | J" | 94.50 | 90.30 | 82.20 | 89.00 | 105.60 | 124.70 | 122.20 | 117.50 |
| % Saturation | (100*J"/I) | | 90.45 | 90.43 | 86.51 | 89.13 | 111.31 | 106.46 | 107.21 | 108.33 |
| % Swell | (100*(E"-E)/E) | | 5.55 | 4.76 | 4.48 | 4.93 | 5.56 | 6.85 | 6.51 | 6.31 |
| Load (lbf) | | P" | 4967.2 | 4972.4 | 4961.1 | 4966.9 | 4969.0 | 4961.7 | 4970.0 | 4966.9 |
| Dry Strength | (2000*P/(pi*t*D)) | Sd | 25304.5 | 25260.5 | 25262.2 | 25275.7 | 25277.2 | 24811.4 | 24849.2 | 24979.3 |
| Wet Strength | (2000*P"/(pi*t"*D')) | Sw | 25029.5 | 24929.0 | 25132.8 | 25030.4 | 25016.4 | 24560.6 | 24869.1 | 24815.4 |
| TSR | (100*(Sw/Sd)) | | | | | 99.0 | | | | 99.3 |